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Prepared for

SPACE DIVISION
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A

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This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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The extragalactic variable radio sources 3C 84, 3C 120, OJ 287, 3C 273, and BL Lac have been observed frequently at 3.3 mm for up to 9 years; the results are compared with 19- , 28- , 38- , and 45-mm observations. 1) The 3-mm variations are often rapid; significant information is lost if observations are not made every 1 - 3 days. 2) The correlation between the 3-mm and centimeter-wave variations of these five sources ranges from high to almost non-existent; in general, the flatter the spectrum, the

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19. KEY WORDS (Continued)

20. ABSTRACT (Continued)

better the correlation. 3) The relationship between time lag and wavelength for possibly-connected outbursts appears to be characteristically different for different objects. 4) No pronounced 3-mm outbursts on a time scale of one to a few days were observed, but three sharp drops or "quenchings" were. A list of other quenchings found in the literature is included. 5) The amplitudes of outbursts vary as λ^{k}, where $\langle k \rangle$ = −0.4, from 3.3 to 111 mm, a factor of 34. Results 4 and 5 may place significant new constraints on models.

PREFACE

M. M. Dworetsky, D. E. Middleton, A. D. Minsk, J. W. Montgomery, and J. D. White provided extensive observing and data reduction assistance during this long effort. R. B. Pomphrey, in addition to extensive observing assistance, made numerous valuable critical evaluations of the calibration procedures. We express our appreciation to many members of the Aerospace Electronics Research Laboratory staff, in particular to G. G. Berry, H. B. Dyson, W. A. Johnson, and T. T. Mori, for the continuing improvements and the efficient operation of the 4.6-m radio telescope. W. A. Burkhalter of the Information Processing Division, and B. S. Ensign, and S. S. Hinatsu, V. Khacherian, and J. H. Petersen of the Art Services Department deserve much of the credit for the multi-color light curves and the three-dimensional plots. J. MacLeod, B. H. Andrew, G. A. Harvey, H. D. Aller, P. E. Hodge, and W. A. Dent provided extensive centimeter-wave data in advance of publication. J. E. Ledden calculated the scaling factor between University of Michigan and Haystack 38-mm data. H. D. Aller, B. H. Andrew, R. Landau, and R. B. Pomphrey made valuable comments on the manuscript.

CONTENTS

FIGURES

TABLES

I. INTRODUCTION

The first observations of extragalactic sources at 3 mm were made with the Aerospace 4.6-m telescope in 1965. At that time longer wavelength data were revealing that many sources were variable and that the variation time scales were often shorter at shorter wavelengths. The Aerospace Corporation had the only facility available on a regular and long-term basis for monitoring at short millimeter wavelengths. Hence we commenced a program of extensive monitoring. The objective was to provide information which could add to the physical understanding of the sources. Results through 1970 were given by Fogarty et al.[1] This report, which is a sequel to and supersedes that paper, presents the results for 3C 84, 3C 120, 3C 273, OJ 287, and BL Lac, the sources we observed most frequently from 1965 through mid-1974. Since then the Aerospace telescope has been utilized for continuum studies of planets and millimeter-wave spectroscopy. We plan to resume source monitoring upon installation of a cooled receiver now under construction.

II. OBSERVATIONS

Fogarty *et al.*[1] and Epstein *et al.*[2] have described the telescope and receiver and the calibration and observing procedures. Here we give only a summary plus some additional relevant details.

A. INSTRUMENTATION AND TECHNIQUE

The observations were made at 3.3 mm (90 GHz) using the "on-on" dual-beam technique. Since March 1969 the telescope tracked a source such that the antenna traced out the identical hour angle arc during the two halves of the "on-on" pair, resulting in cancellation of antenna sidelobe and backlobe pickup of the atmosphere and ground. Data prior to March 1969 were corrected for incomplete cancellation.[1] Each observation consisted of $\approx$ 10 hours of integration separated into $\approx$ 25-min segments which were reduced individually and then averaged together; the integration time was generally spread out over a few days in an attempt to randomize the effects of any unknown systematic errors which might vary from day to day.

Correction factors to the measured flux densities for pointing errors (not corrected for while observing) and antenna jitter ranged from $\approx$ 1.01 to $\approx$ 1.10. Antenna pointing information prior to 1971 was derived from frequent measurements of the limbs of the Sun; subsequently both solar limb measurements and planet measurements by a five-point-grid procedure (FIVE) were used. The FIVE procedure is the preferred method for observing stronger sources, such as the planets, because the information for correcting the measured value for pointing errors is contained in the measurement itself.

B. CALIBRATION

The variation of antenna gain as a function of zenith angle was determined from 862 FIVE measurements of Venus and Jupiter taken from 1971 through 1977. The derived gain relative to the zenith value (e.g., 0.923 $\pm$ 0.010 at z = 60 deg) agrees to within 1 - 2% with that predicted from reflector surface accuracy measurements at various zenith distances.

The Sun was the primary standard of antenna temperature. A gas tube was the intermediate standard prior to November 1968, and a hot resistive load thereafter; the measurements of the load were corrected for ambient temperature effects subsequent to data acquisition. The intermediate standard was calibrated against the Sun's 90-GHz brightness temperature of 7820 K[2] by the average intercept method.[3]

The relationship of flux density to antenna temperature was determined by comparing the average of 29 observations of DR 21 taken from 1967 to 1975 (Fig. 1) with the calibrated 90-GHz DR 21 flux density of 17.7 ± 0.5 Jy; Ulich* has subsequently revised this value to 17.3 ± 0.6 Jy but we have not made a corresponding revision in our calibration. A factor of 1.016 was used to correct the flux density of DR 21 for the effects of beam broadening by the Aerospace telescope. The net overall absolute calibration uncertainty in our results is estimated to be ≈ 7%.

C. SYSTEM CHECKS

Because the observations reported here are measurements relative to an internal intermediate standard, rather than measurements relative to standard sources on the sky, we performed the following checks on system calibration and performance:

(i) The histogram of the ≈ 25 antenna temperature measurements comprising each observation was inspected to verify that the dispersion in the measurements was consistent with receiver noise.

(ii) Over the years we have made hundreds of observations of "blank" sky (e.g., see Fig. 8 of Ref. 4 and Fig. 1 of Ref. 5) to confirm repeatedly that our system introduces no measurable biases.

(iii) We verified the reliability of Sun-derived pointing information by comparing planetary brightness temperatures obtained by using pointing corrections determined only from Sun measurements with temperatures obtained by using the preferred FIVE procedure. Any systematic differences between

*Private communication

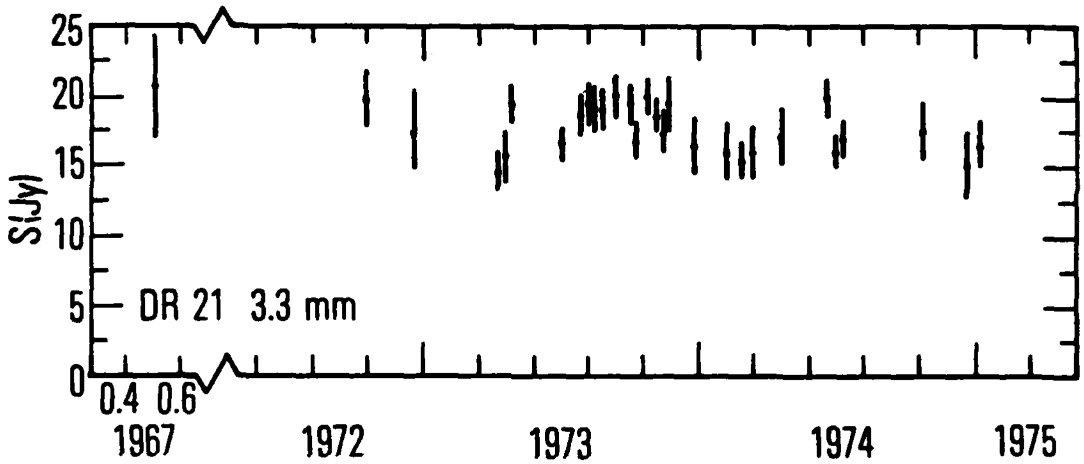


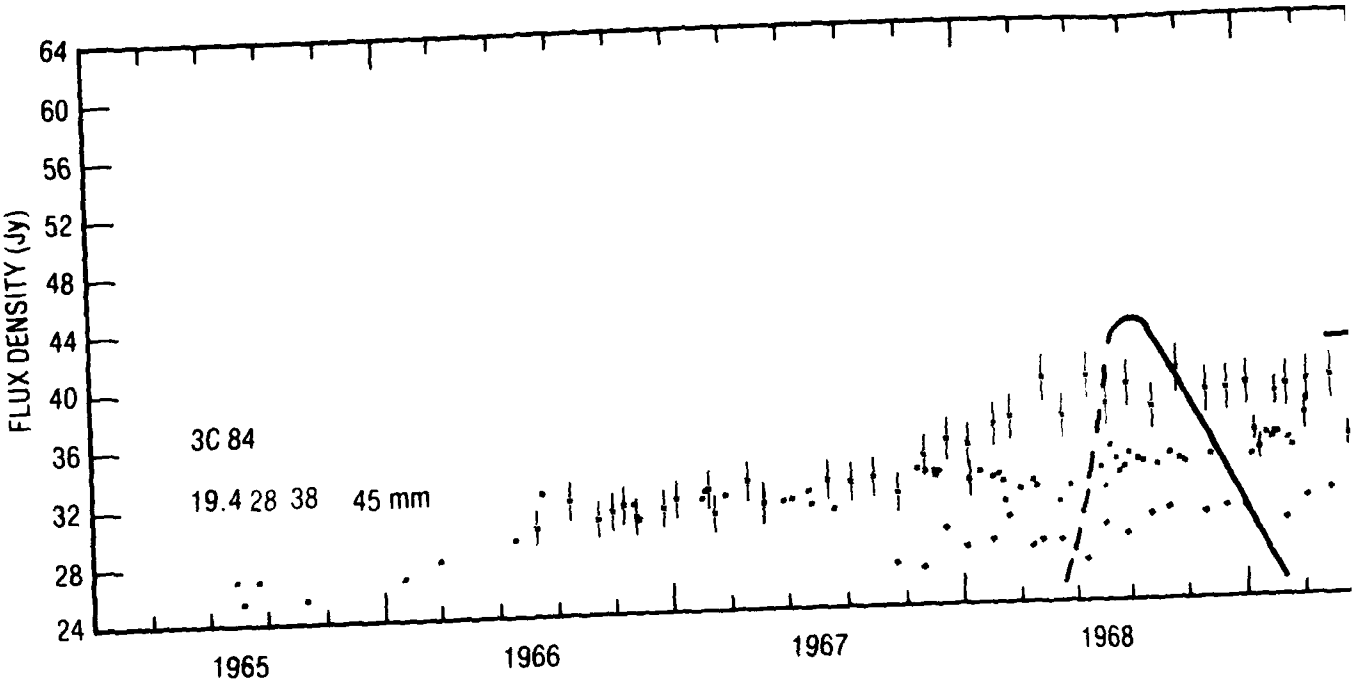
Figure 1. Flux density at 3.3 mm vs. time for the reference source DR 21. The 1-σ relative error bars are shown. The scatter in the data is entirely consistent with measurements of a constant source.

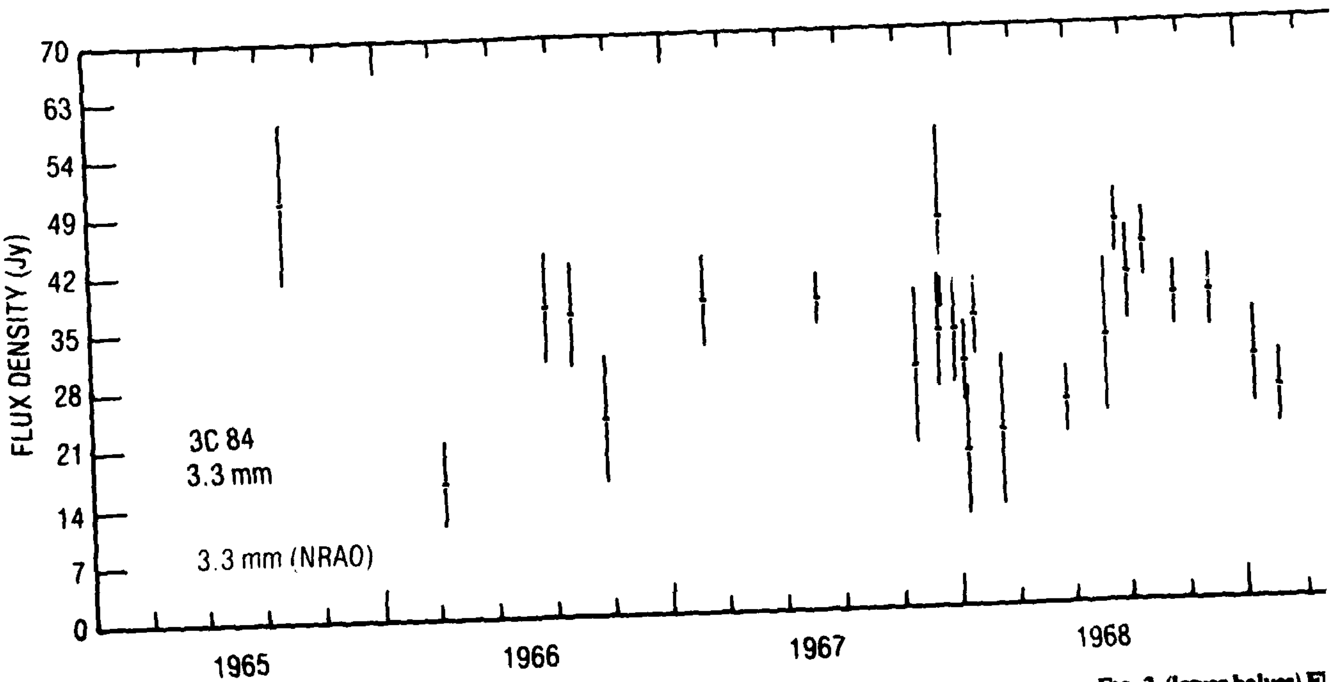
temperatures obtained before and after the introduction of the FIVE procedure are $\lesssim$ 3% (see Fig. 1 of Ref. 2).

(iv) The repeatability of the measurements is shown in the display of the DR 21 data (Fig. 1). Even though these data suggest an outburst of 2 - 3 Jy amplitude during the second half of 1973, the scatter about the mean value is entirely consistent with the 1-σ error bars; furthermore there were no comparable percentage variations in our 1973 Jupiter and Saturn data (see Fig. 1 of Ref. 2), indicating that there was not a multiplicative error in all of our data.

(v) We inspected all the data for coincidental rises and declines with the aid of a procedure similar to that of Kesteven _et al._[6] During only one interval (approximately 5 weeks in the spring of 1972) did all five sources exhibit the same pattern--simultaneous rises by an average of 12%. These _simultaneous_ rises are so unlikely that we assumed the presence of an unknown systematic error and reduced all readings during that interval by 12%.

(vi) Numerous comparisons with independent 3-mm measurements obtained with the NRAO 11-m telescope by Hobbs and Dent[7] are presented in the lower portions of Fig. 2, where the NRAO 3-mm measurements are shown as red triangles (the height of each triangle corresponds to twice the 1-σ error). The Hobbs and Dent data have been multiplied by the factor 1.047 to account for their adoption of a DR 21 flux density of 16.9 Jy instead of the 17.7 Jy used here. The overall agreement between the two completely independent sets of data is excellent.





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(upper halves) Centim
error bars indicate 1σ r
twice the height of the
the symbol or smaller)

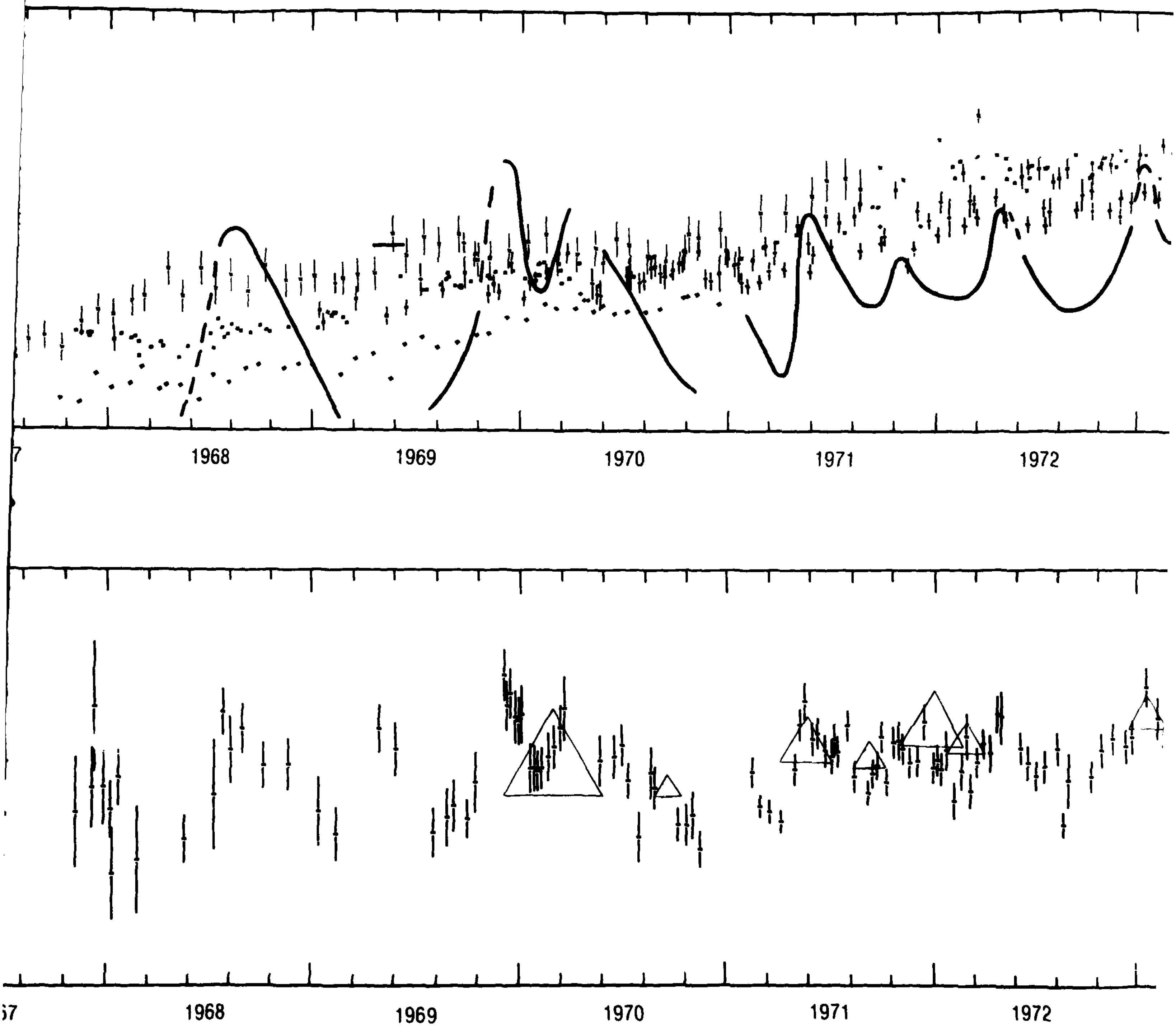
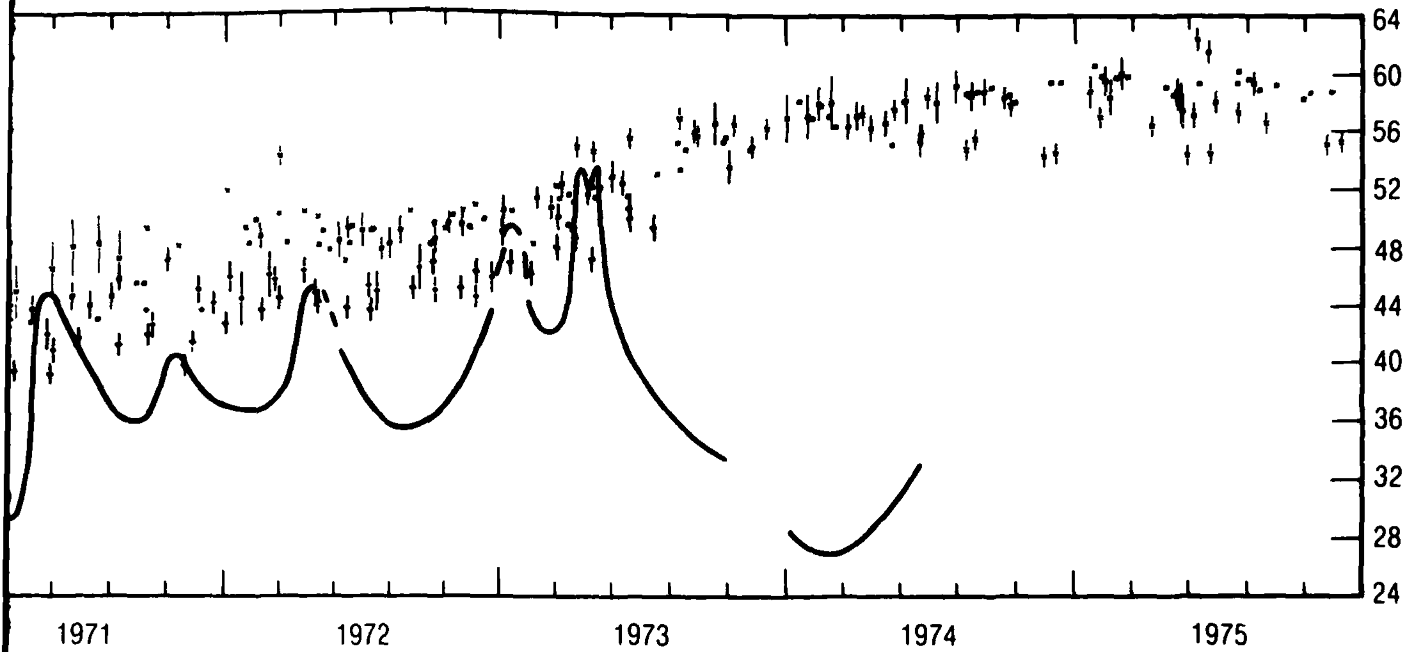
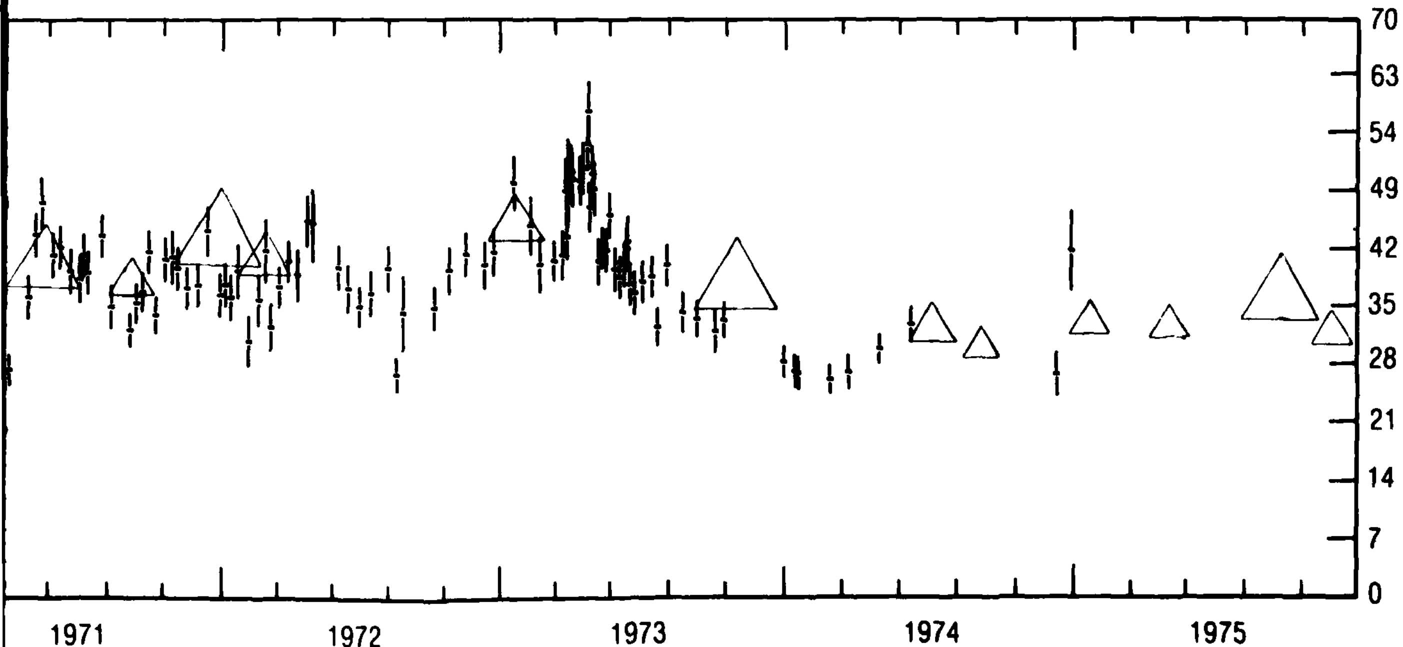


FIG. 2. (lower halves) Flux density at 3.3 mm vs time. The error bars indicate the 1σ relative uncertainties only; the estimated overall absolute calibration uncertainty is 7%. The red triangles represent 3-mm data obtained by Hobbs and Dent (1977) with the NRAO 11-m antenna; their height corresponds to twice the 1σ relative measuring error. (upper halves) Centimeter-wave flux densities vs time plus hand-drawn representations of the 3.3-mm data. The error bars indicate 1σ relative uncertainties. To avoid overcrowding, error bars are omitted when they are less than twice the height of the symbol (thus the absence of an error bar does not automatically mean the error is the size of the symbol or smaller). Note that the intensity scales for the upper and lower halves are different.





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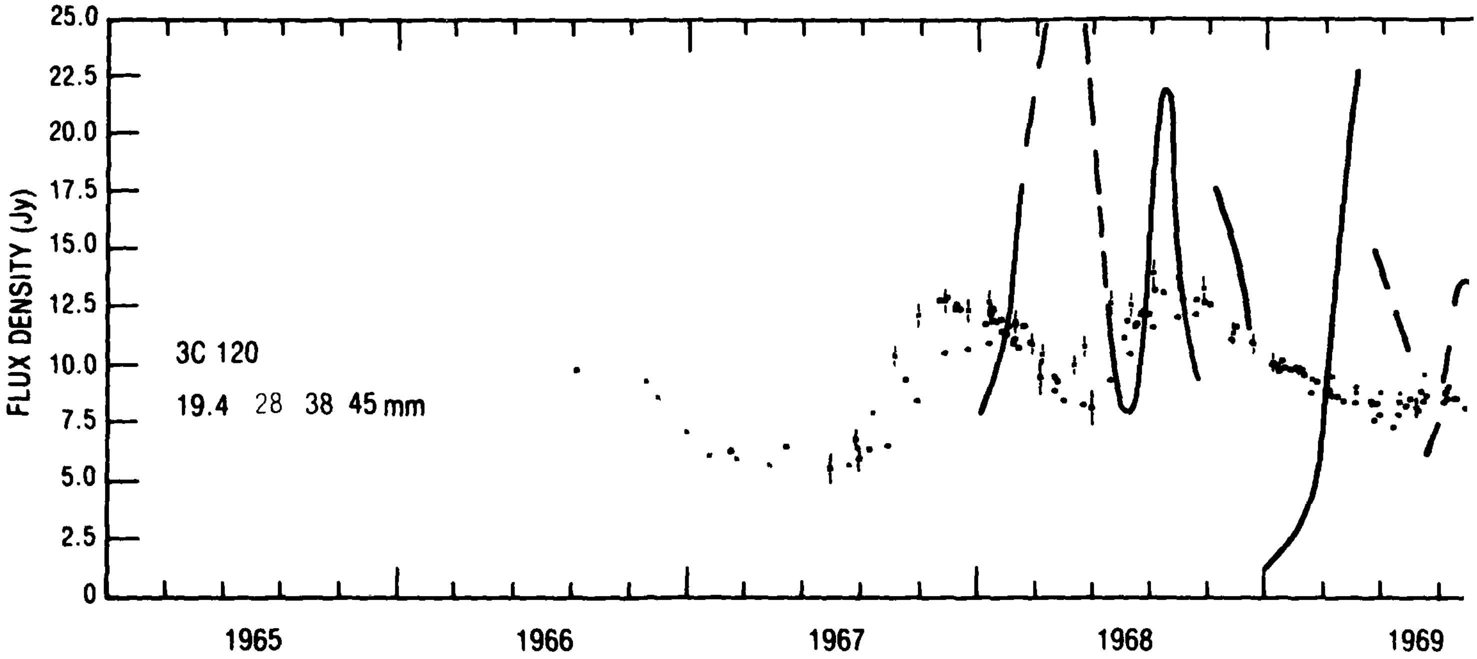
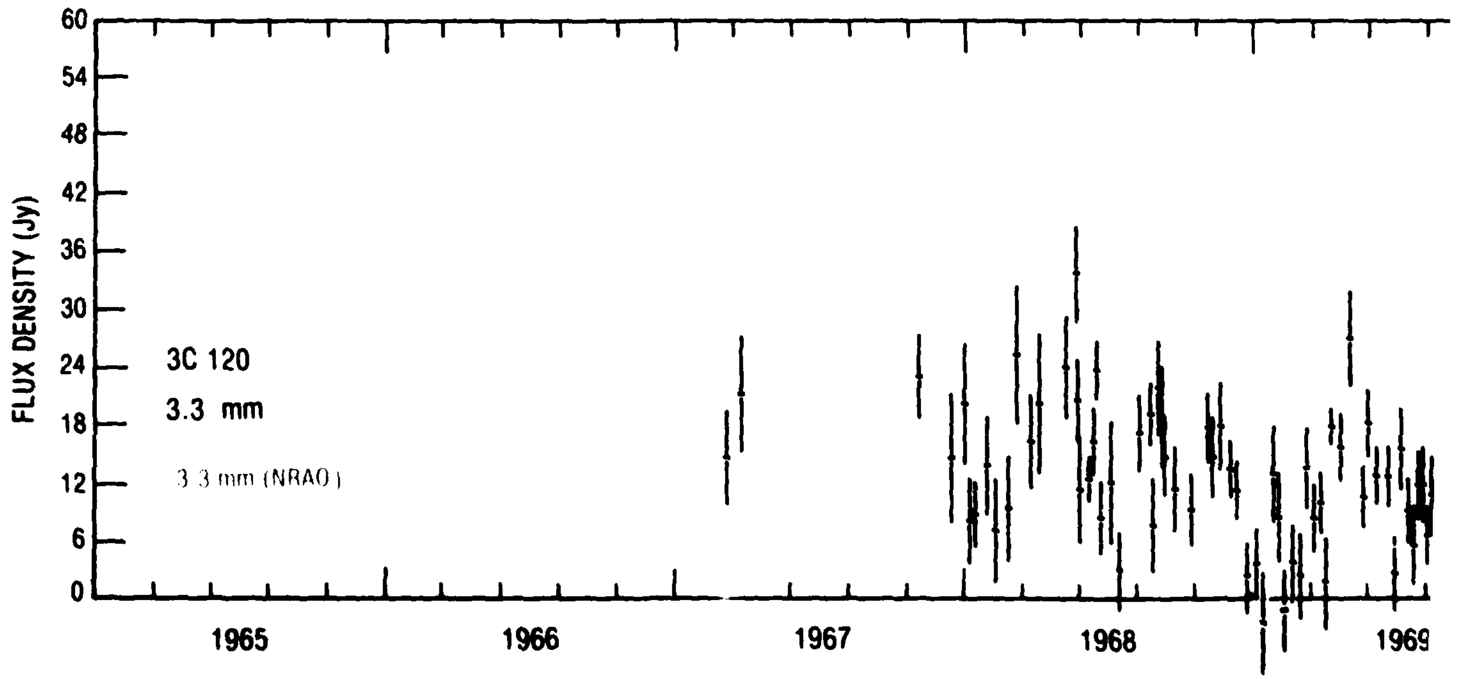
3


25.0
22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0
FLUX DENSITY (Jy)
3C 120
19.4 28 38 45 mm
1965
1966
1967
1968
1969


60
54
48
42
36
30
24
18
12
6
0
FLUX DENSITY (Jy)
3C 120
3.3 mm
3.3 mm (NRAO)
1965
1966
1967
1968
1969

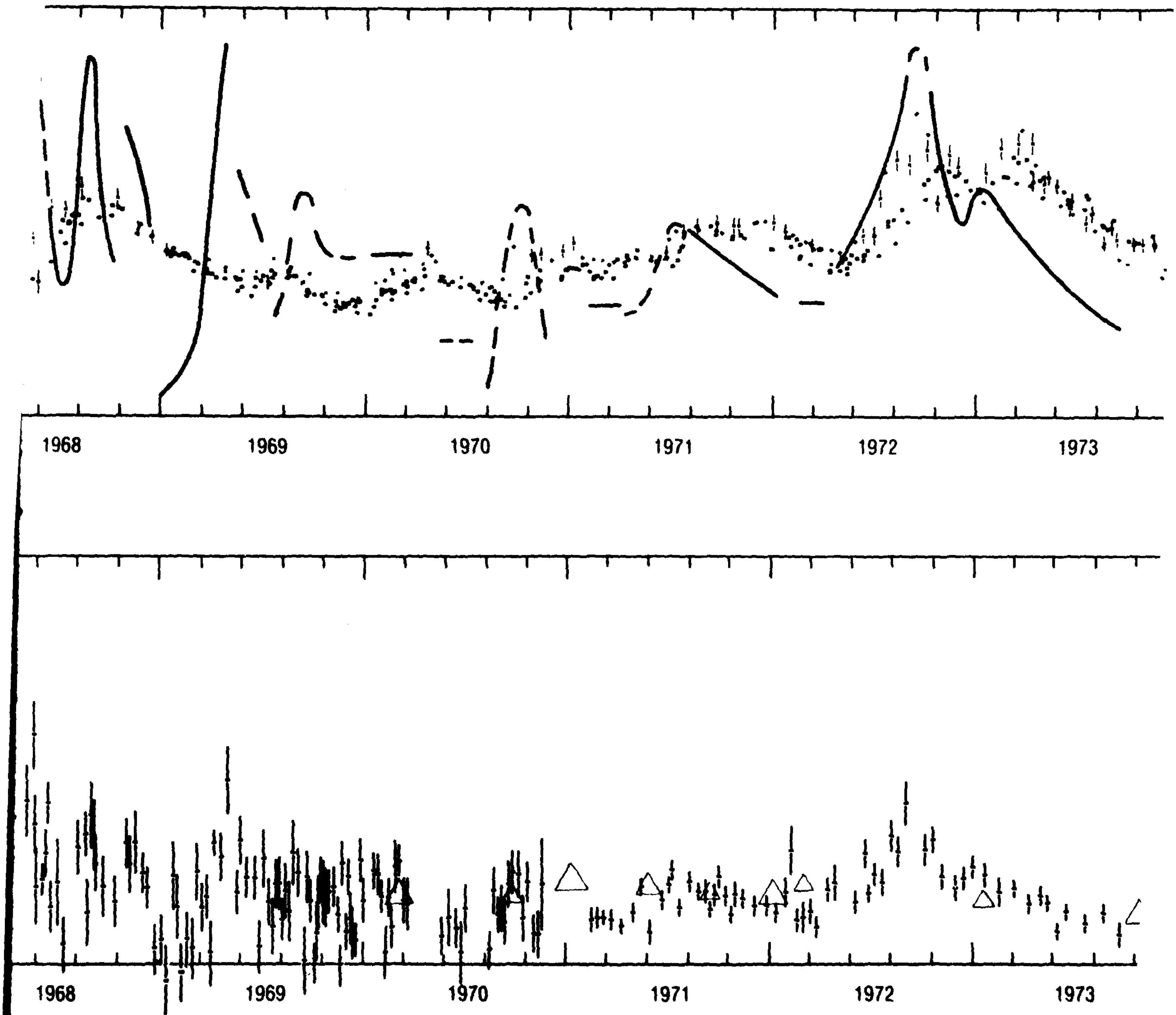
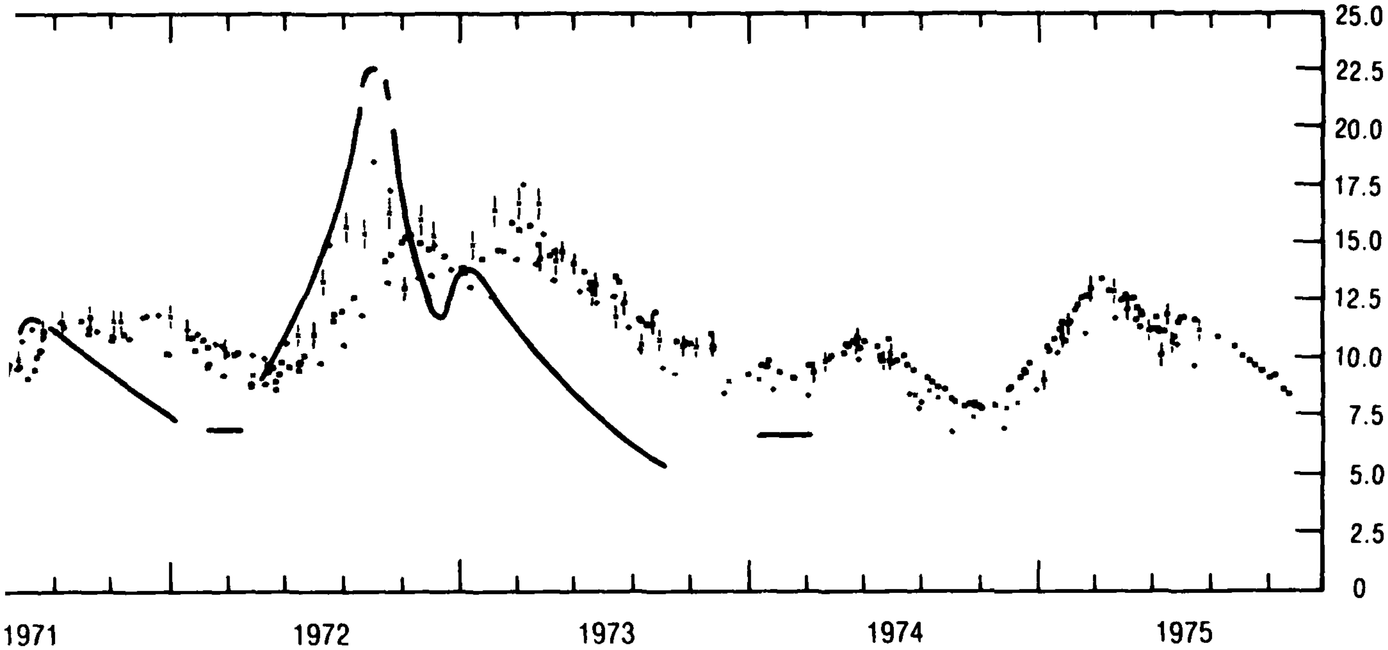
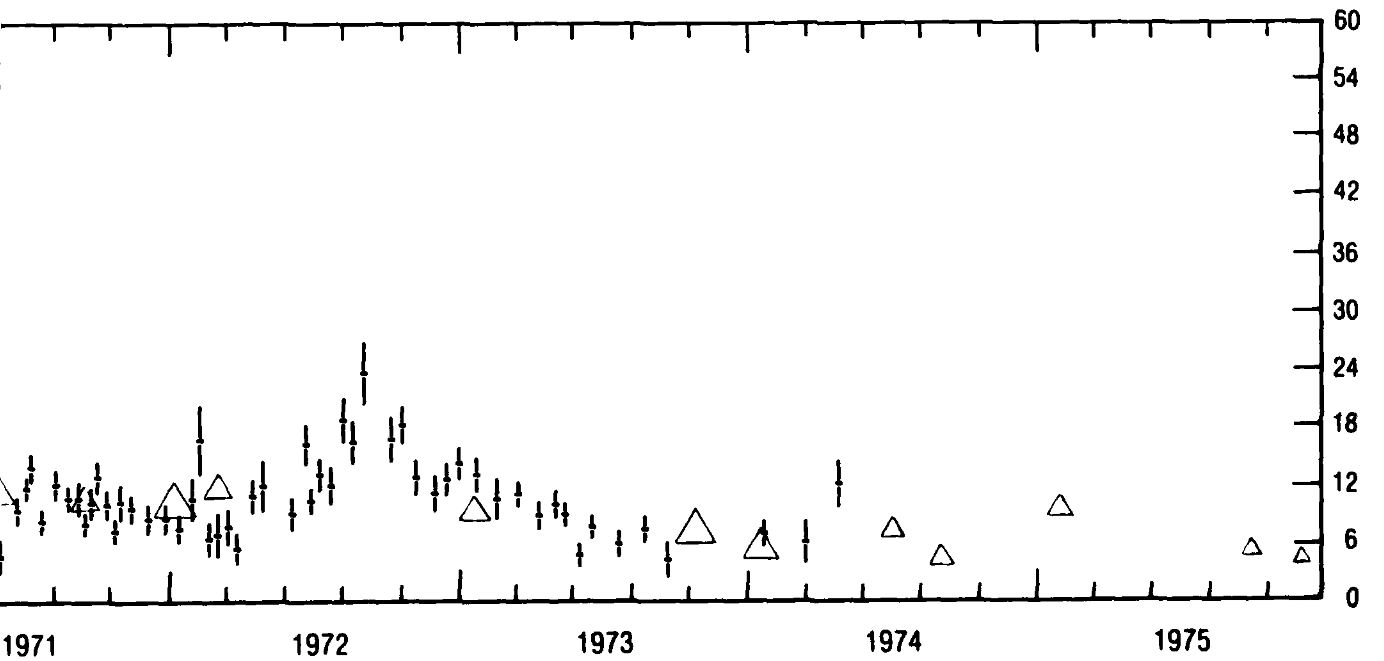


FIG. 2. (continued)

2





3

p. 452B (3C 120)

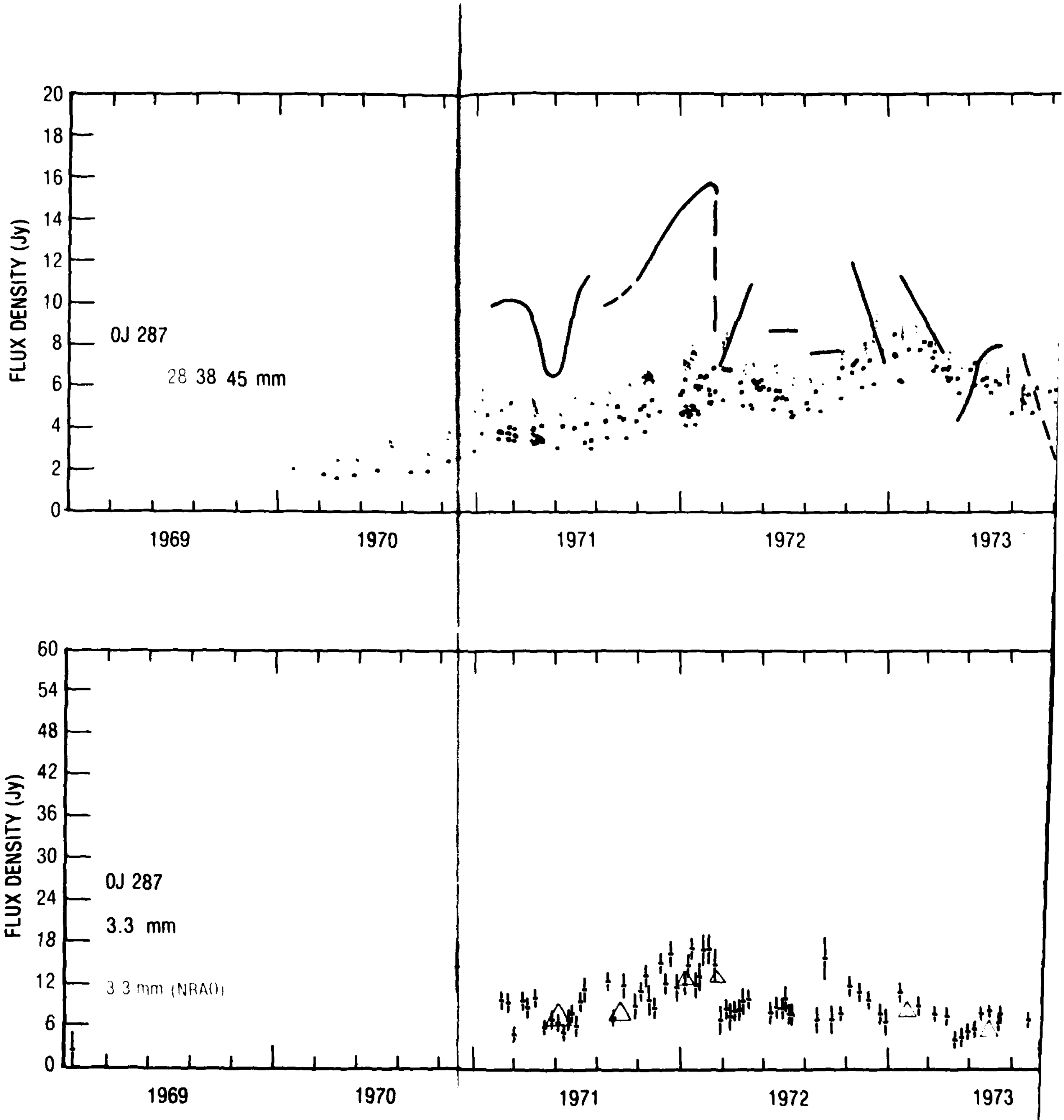
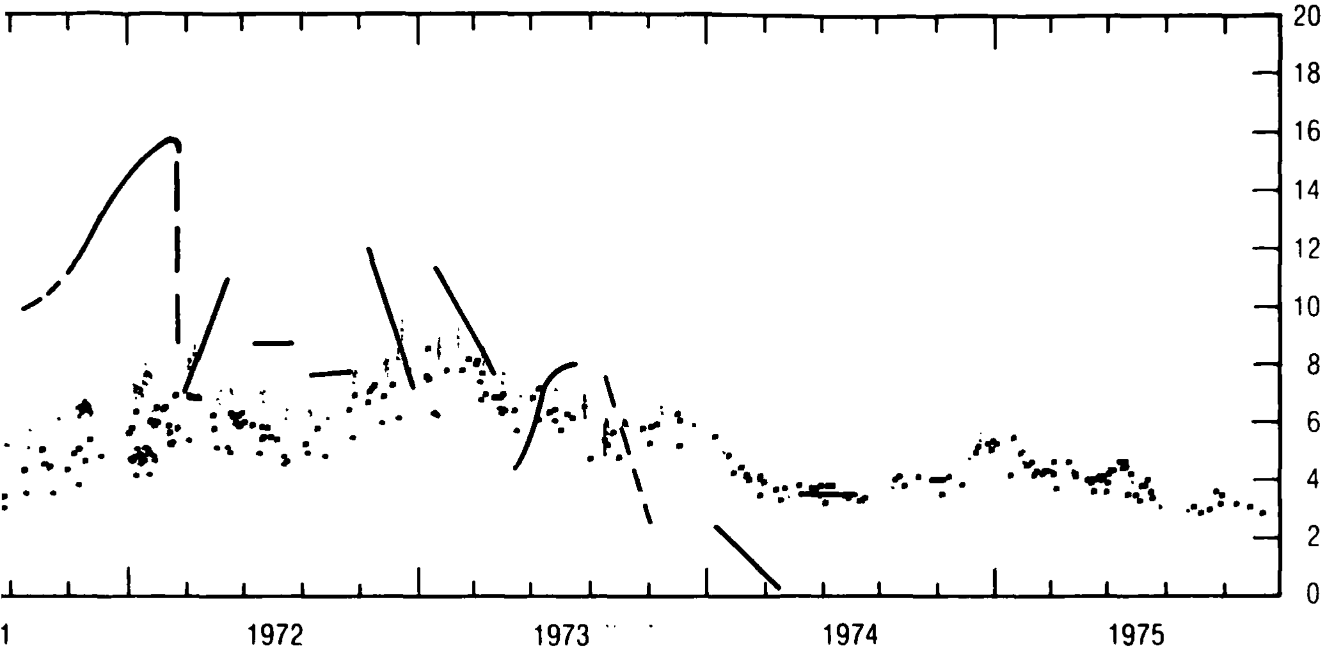


FIG. 2. (continued)



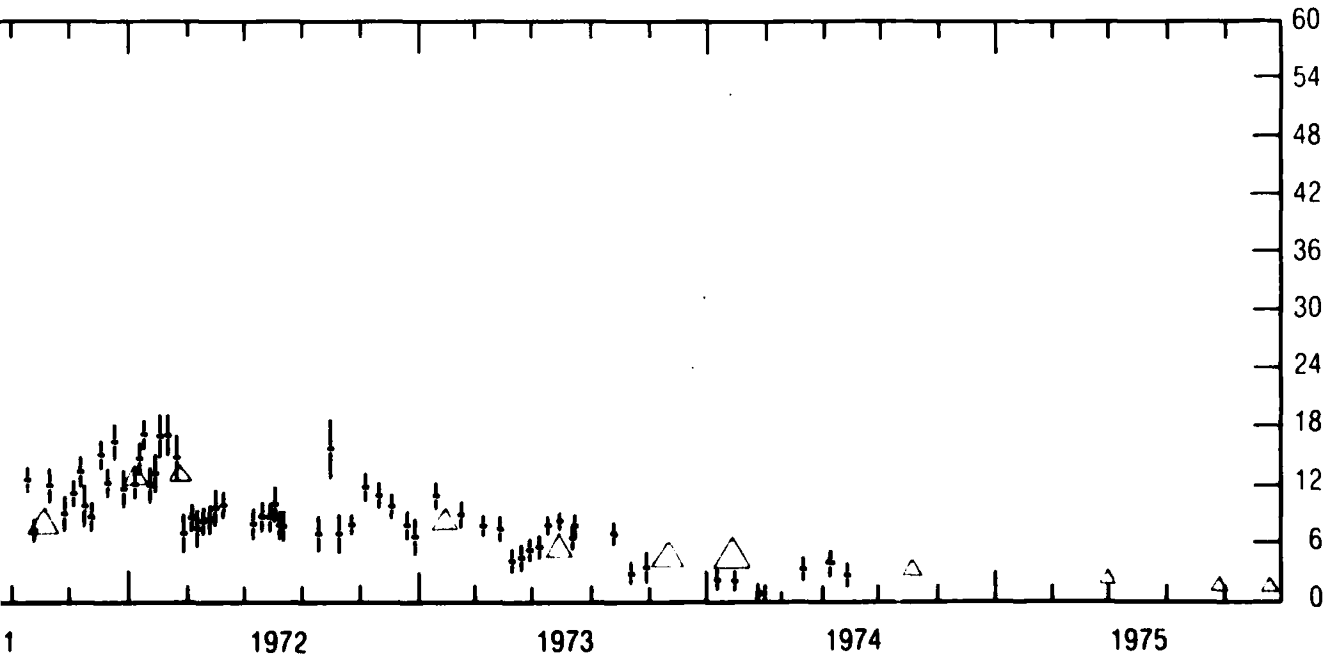
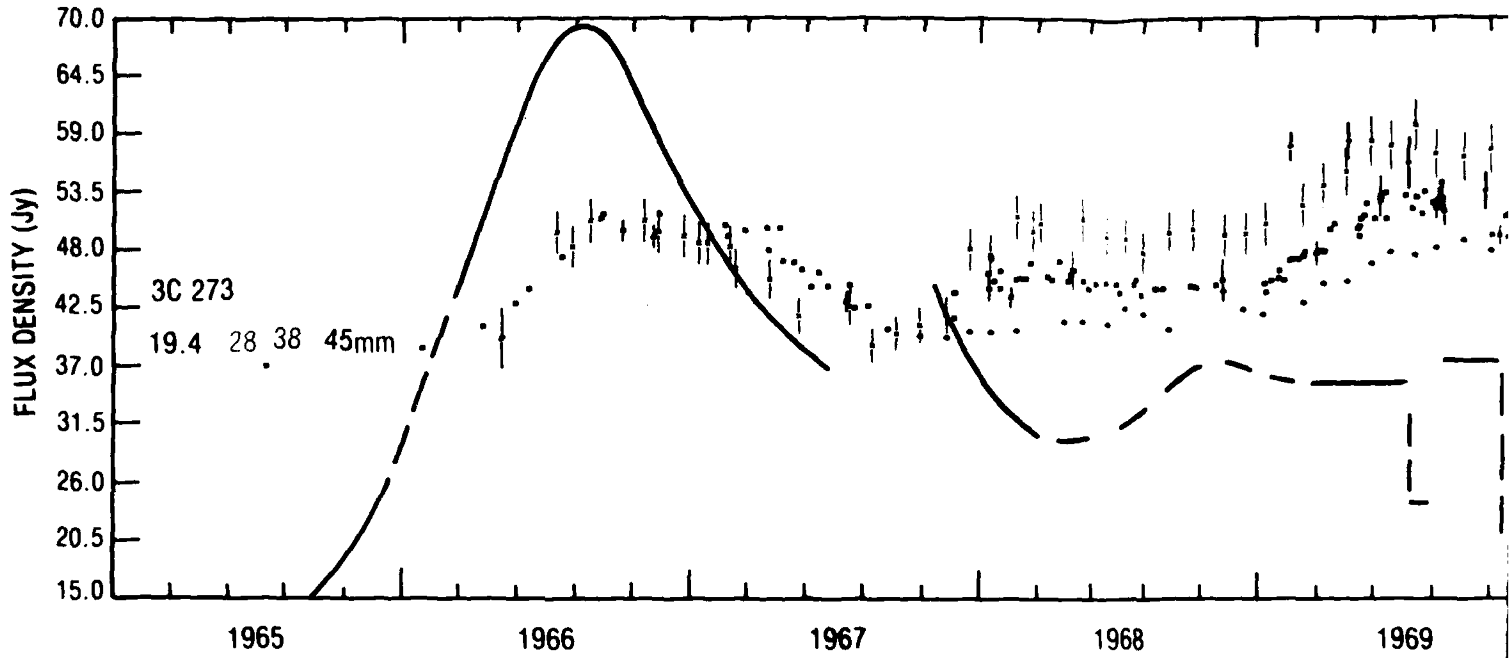
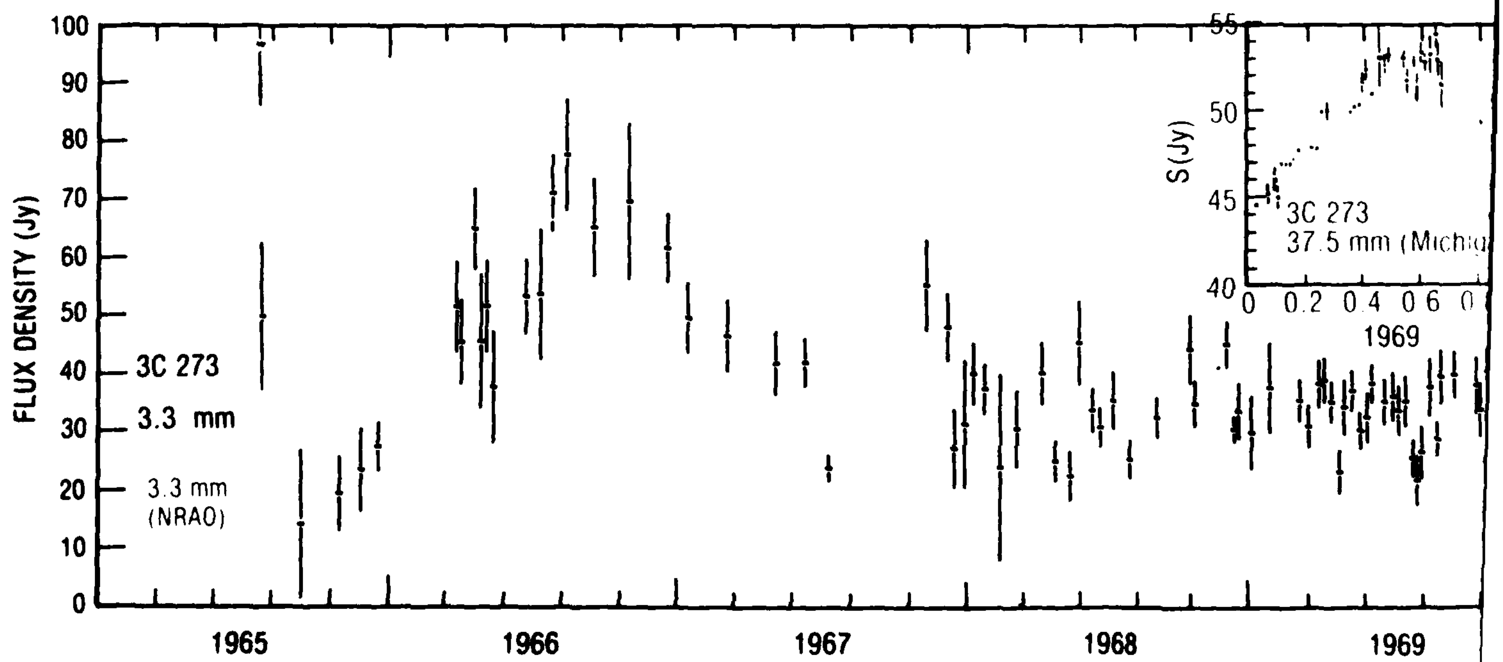


FIG. 2. (continued)



FLUX DENSITY (Jy)
3C 273
19.4 28 38 45mm
1965
1966
1967
1968
1969



FLUX DENSITY (Jy)
3C 273
3.3 mm
3.3 mm (NRAO)
S(Jy)
3C 273
37.5 mm (Michig
1969
1965
1966
1967
1968
1969

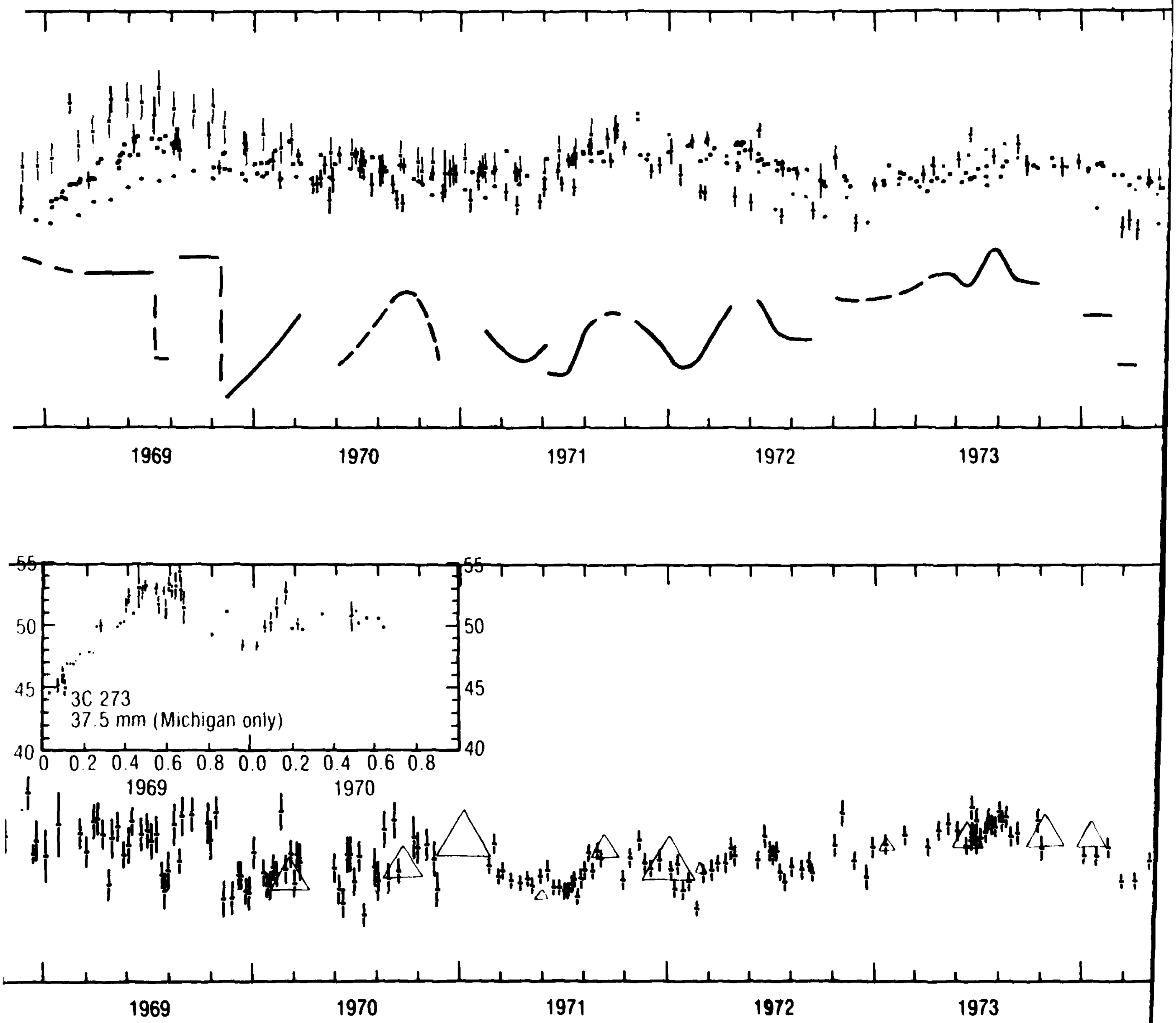
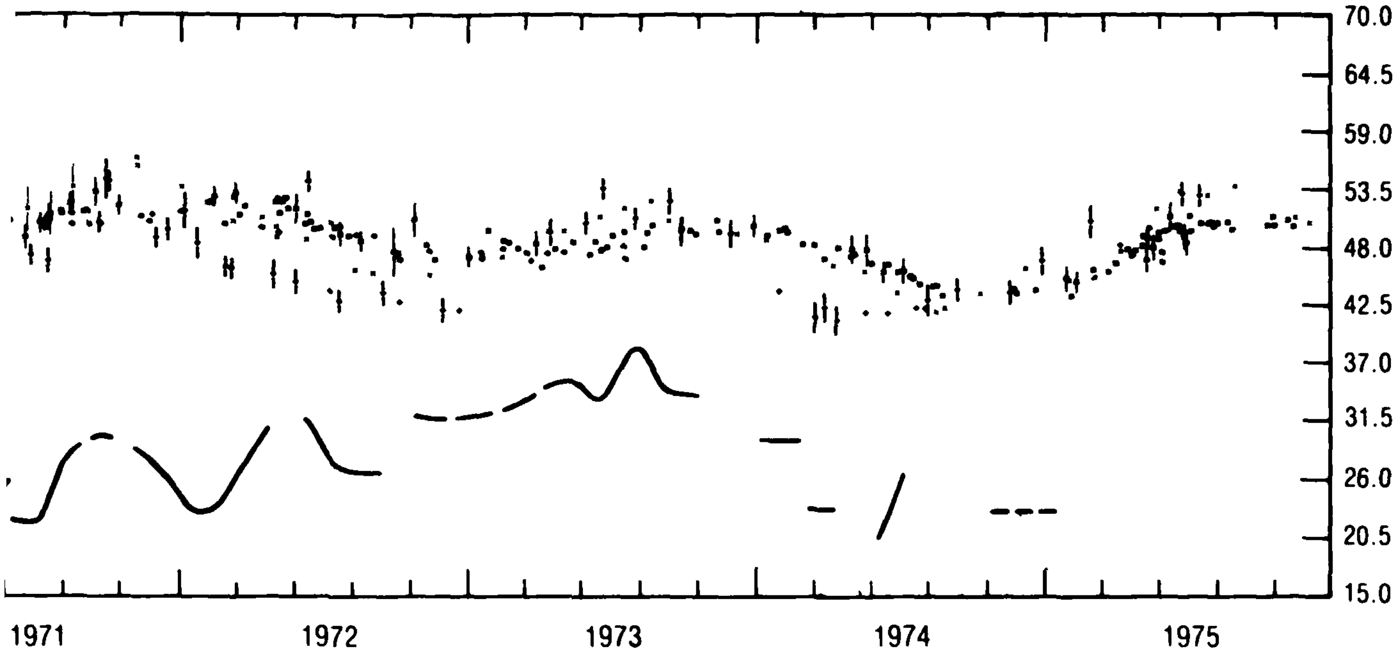
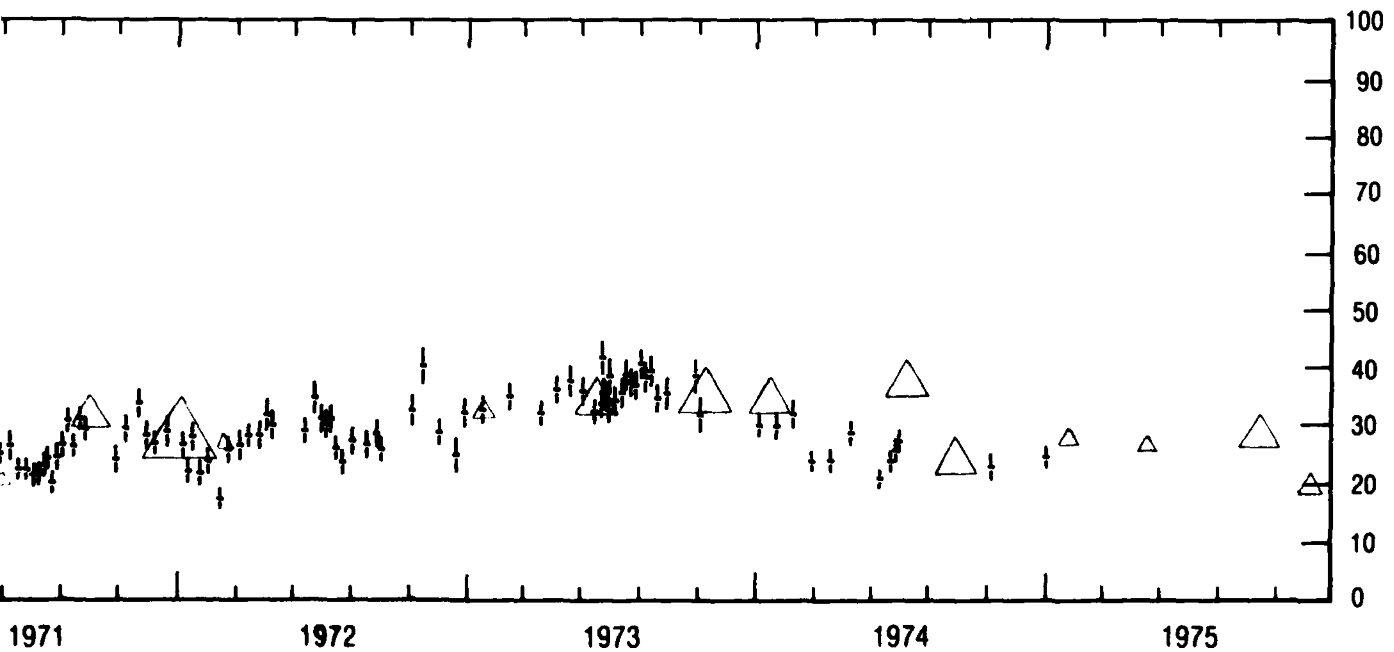


FIG. 2. (continued)

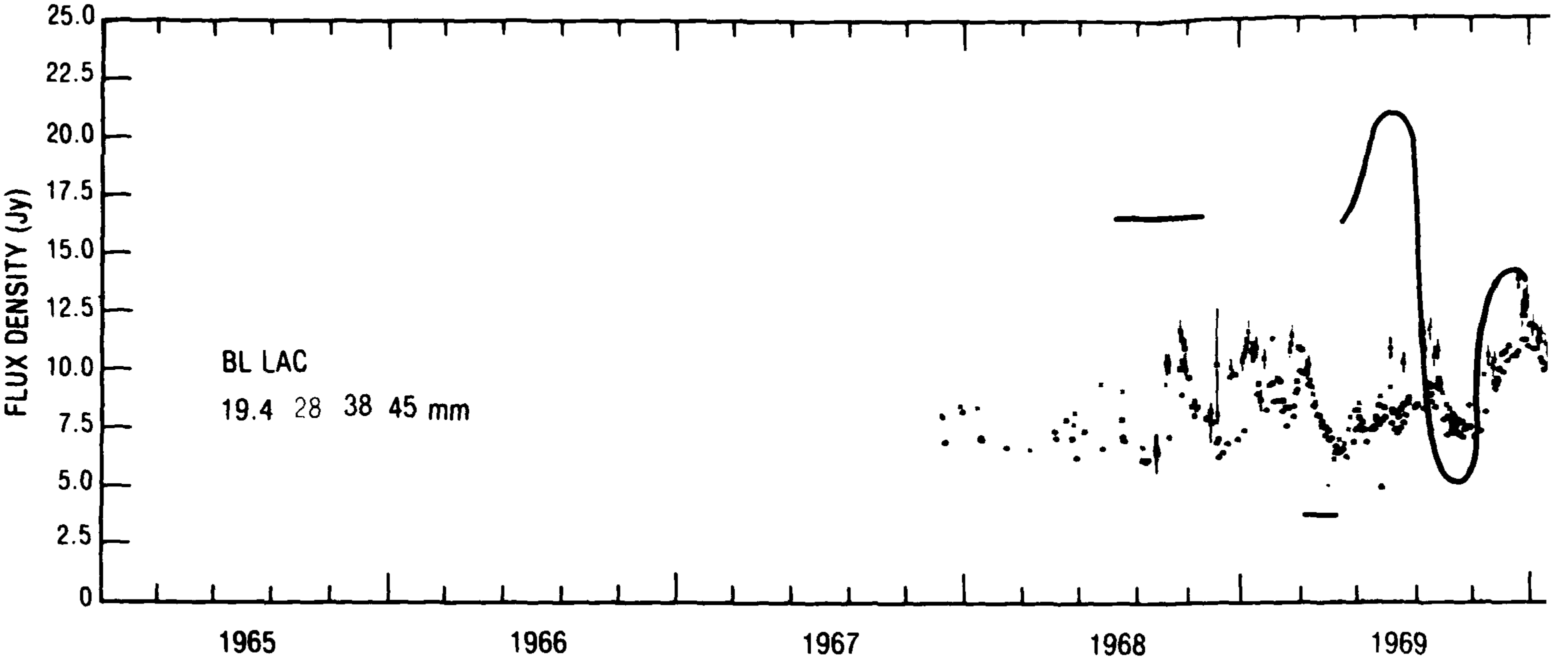
2

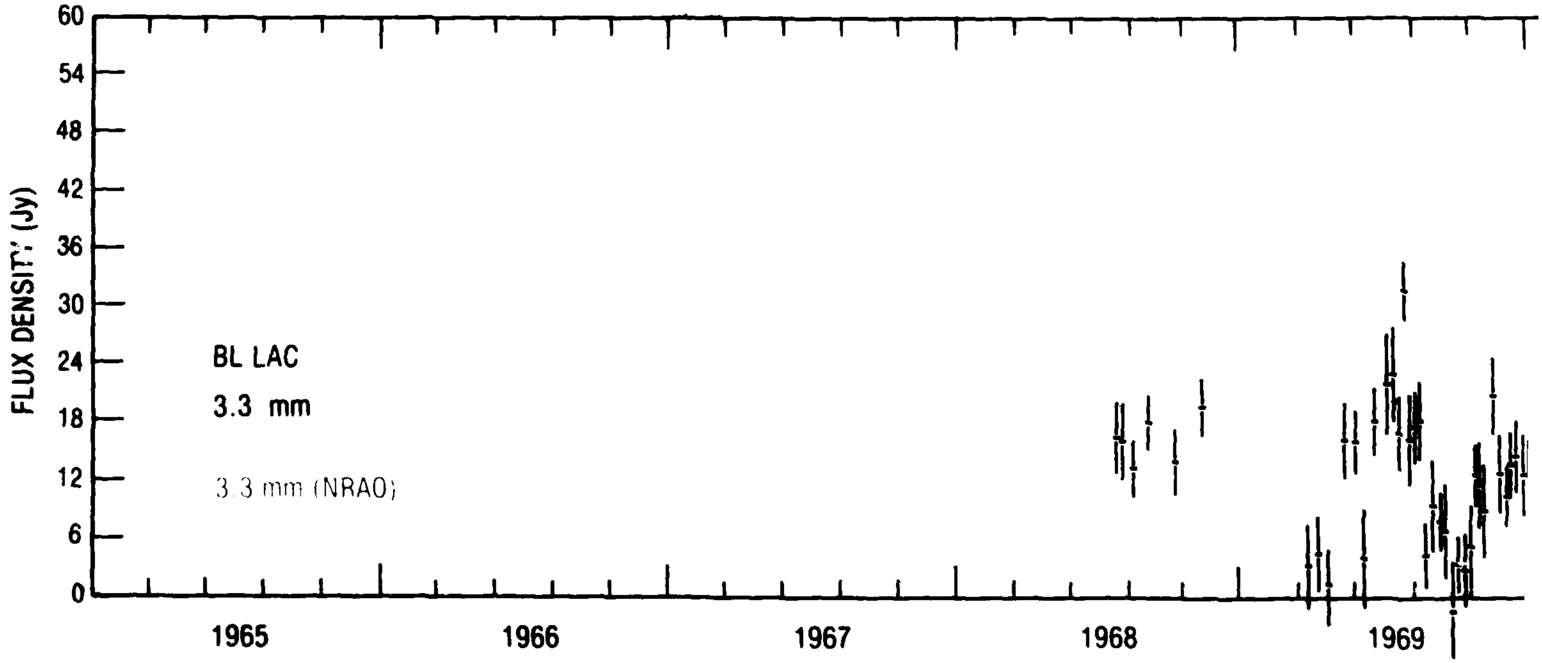




3

p. 452D (3C 273)


25.0
22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0
FLUX DENSITY (Jy)
BL LAC
19.4 28 38 45 mm
1965
1966
1967
1968
1969


60
54
48
42
36
30
24
18
12
6
0
FLUX DENSITY (Jy)
BL LAC
3.3 mm
3.3 mm (NRAO)
1965
1966
1967
1968
1969

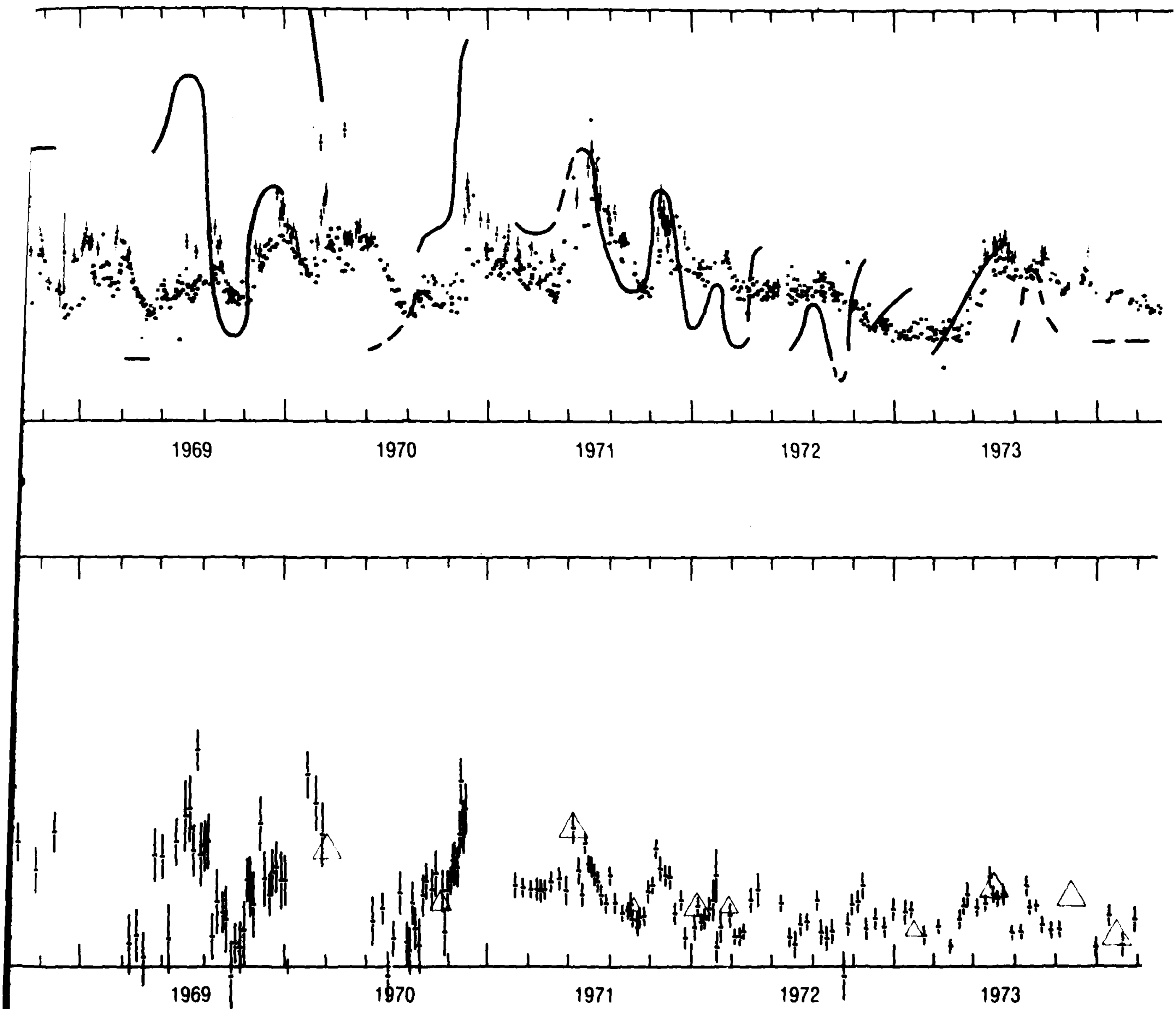
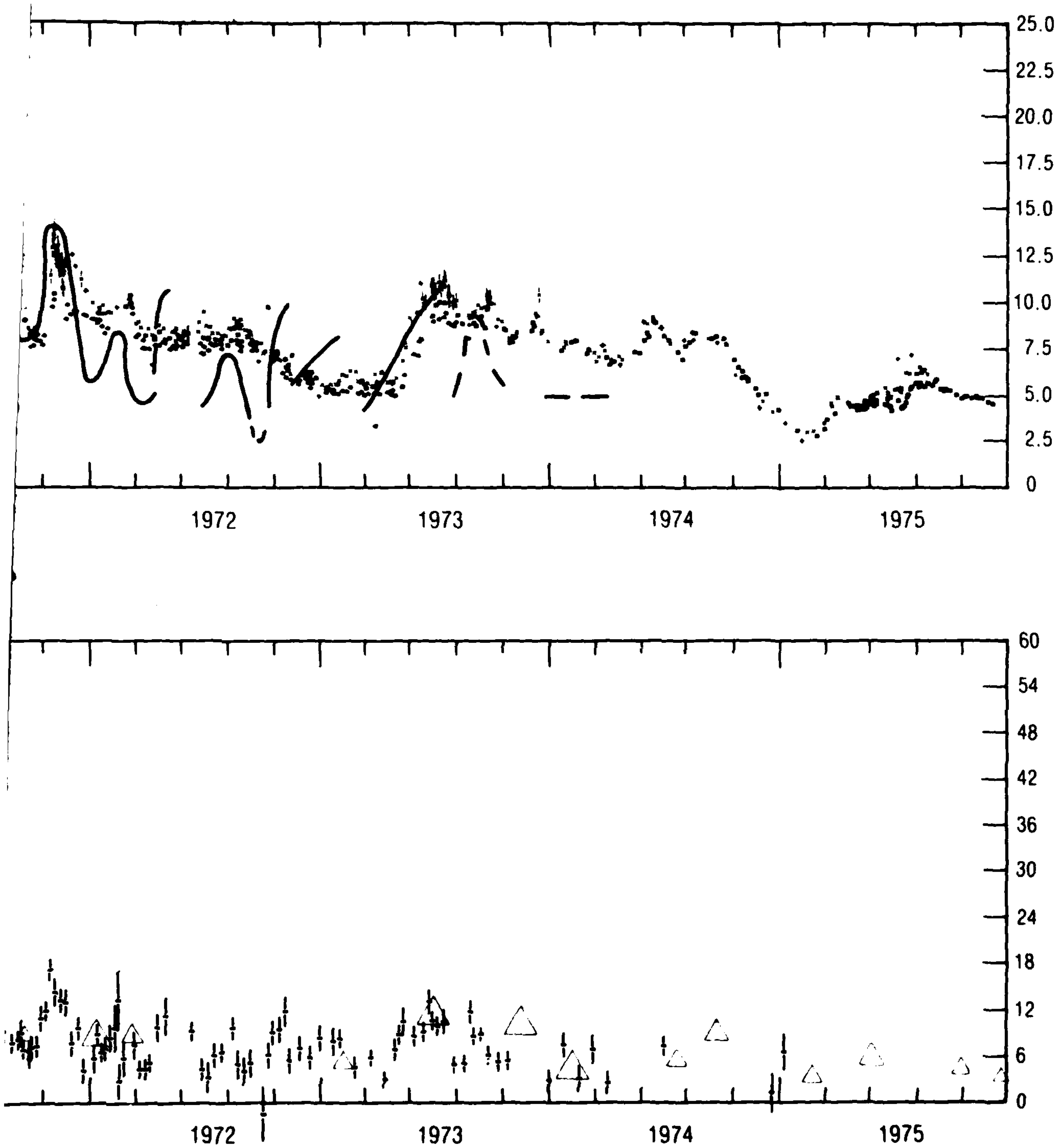


Fig. 2. (continued)

2


25.0
22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0
1972
1973
1974
1975
60
54
48
42
36
30
24
18
12
6
0
1972
1973
1974
1975

p. 452E (BL Lac)

III. RESULTS

The adopted calibration factors, attenuation correction schemes, and data reduction procedures changed several times over the years. To assure uniformity of data handling, we re-reduced all 9 years of data for 3C 84, 3C 120, 3C 273, OJ 287, and BL Lac, the five most frequently observed sources; the results here supersede those published earlier.[1] (The data for many other less frequently observed sources[1] have not been re-reduced.) The results are listed in Table I and are shown in the lower halves of Fig. 2. The 1-σ error bars shown indicate only the relative errors of measurement. The pronounced reduction in the errors beginning in 1971 was due to major receiver improvements, including the installation of a dual IF system.

In the upper halves of Fig. 2 we used black curves to show subjective representations of the 3-mm data (showing the actual data points would have overcrowded the figure); we used dashes where the data are sparse. We have been cautious in drawing these representations — the DR 21 results indicate that there can be spurious variations of 2 - 3 Jy amplitude in our results (see Sec. II.C.iv). So the reader may make an unbiased interpretation of the data[8], we have not drawn curves through the actual 3-mm data in the lower halves of Fig. 2.

Table I. 3.3-mm Observations[a]

START	END	⟨S⟩ (Jy)	σ (Jy)
3C 84			
[illegible]	[illegible]	[illegible]	[illegible]
3C 120			
[illegible]	[illegible]	[illegible]	[illegible]
OJ 287			
[illegible]	[illegible]	[illegible]	[illegible]
3C 273			
[illegible]	[illegible]	[illegible]	[illegible]
BL Lac			
[illegible]	[illegible]	[illegible]	[illegible]

[a]EACH LINE CONTAINS THE START AND END DATES, THE MEAN FLUX DENSITY, AND THE STATISTICAL STANDARD ERROR OF THE MEAN OF AN OBSERVATION

IV. CENTIMETER-WAVELENGTH DATA

These 3-mm results are the largest available set of millimeter monitoring data with high temporal resolution. To facilitate comparisons with longer wavelength data, we also show in Fig. 2 the four sets of centimeter-wavelength data which have the most nearly comparable resolution. No similar body of monitoring data exists between 3 and 19 mm. The 1.94-cm data are from Ref. 9 and private communication with Dent; the 2.8- and 4.5-cm data are from Ref. 8; the 3.8-cm data are from Refs. 10 through 12 and private communication with Aller. Aller's flux densities were multiplied by 1.044, the factor derived by Ledden* to bring into agreement the Michigan and Haystack scales for these data. Altschuler and Wardle, who used the NRAO 3-element interferometer, did not observe 3C 273; and we have not used their 3C 84 results because they did not agree with near-simultaneous Haystack and scaled Michigan 3C 84 data. The disagreement is probably accounted for by uncertainties in the gain-elevation curve for the interferometer at small zenith angles.[12,13]

The centimeter data are shown in the upper halves of Fig. 2. To avoid overcrowding the 1-σ error bars are omitted when they are less than twice the height of the symbol (the absence of an error bar does not necessarily mean the error is as small as or smaller than the size of the symbol).

Because there is so much information in Fig. 2, we sought alternate presentation modes to provide a succinct way to see the time and frequency relationships. The 3-dimensional plots in Fig. 3 are one result. These plots are sequences of spectra. The identical data for each source are shown from two aspect angles. There is some loss of information because the light curves had to be smoothed and then sampled at uniform intervals (0.02 years) to prepare the plots. But they do give a "global" impression of the behavior of the sources. Caution: this presentation mode does not indicate the uncertainties in the data.

*Private communication.

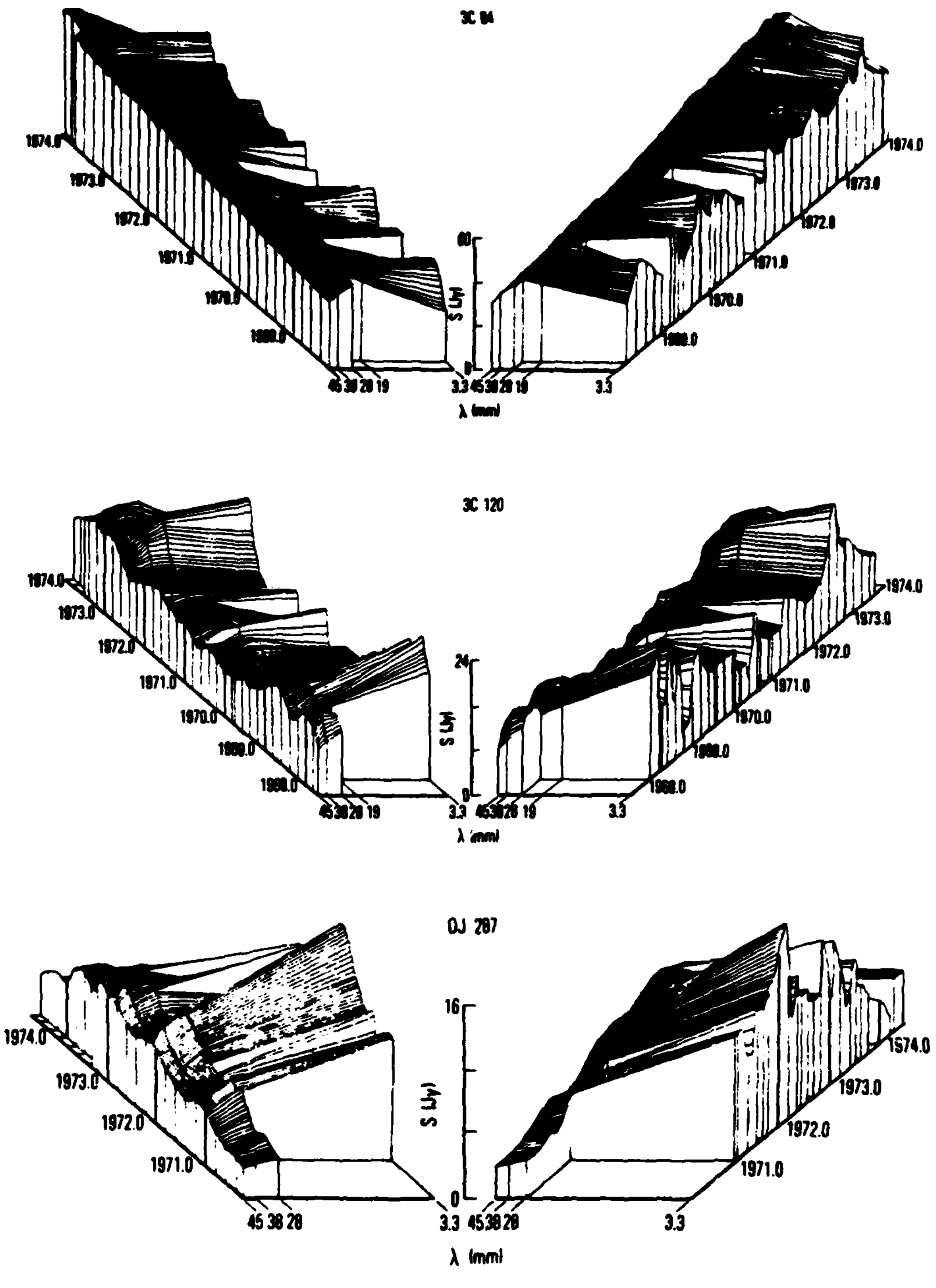


Figure 3 Three-dimensional plots of the data from Fig. 2. Curves have been drawn by eye through the data; the curves have then been sampled at intervals of 0.02 years to obtain the data for these plots. These three-dimensional presentations amount to sequences of spectra. The same data are shown from two aspect angles. Caution: these plots do not portray the uncertainties in the data.

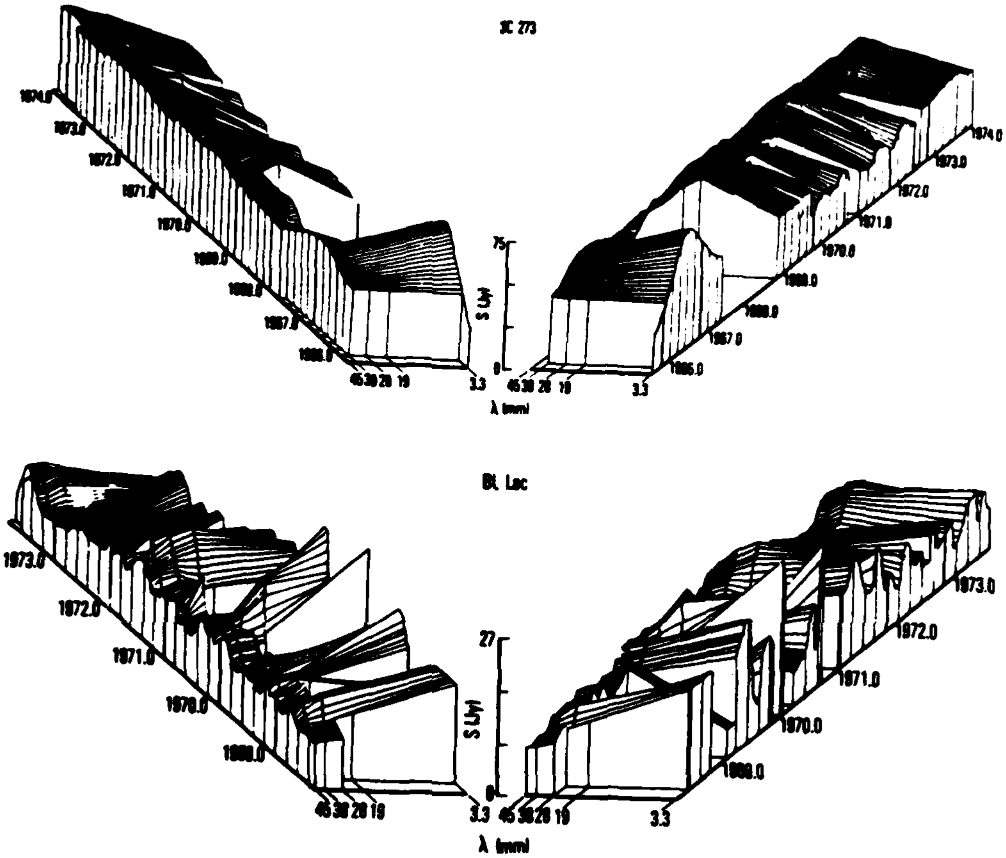


Figure 3. (Continued)

V. DISCUSSION

A. POSSIBLE CONNECTIONS BETWEEN EVENTS AT DIFFERENT WAVELENGTHS

Table II lists by date and wavelength all of the outbursts (defined as a rise and fall) that we have discerned in Fig. 2. The table also includes three sharp drops (see Sec. V.E). We have studied Fig. 2 extensively to discern more than just the obvious possible connections between events at different wavelengths. Possible connections are identified by entering the dates of the events on the same line in Table II. The criteria used in identifying connections included time coincidence or time lag (we assumed that the conventional adiabatic expansion model pertains and thus we excluded the possibility of events at longer wavelengths occurring earlier), similarity of the shapes of the light curves, and relative amplitude. We considered links only between the events nearest in time — i.e., we did not consider the possibility of "leapfrogged" events.

Caveats: Subjectivity is involved in identifying events; even more subjectivity is involved in making connections. This subjectivity emphasizes the need for signatures, such as Stokes parameters, in addition to total intensity as a function of time, to identify the same outburst at different wavelengths. Furthermore, it is possible that two closely-spaced 3-mm events may merge at longer wavelengths into a single event. It is also possible that some events observed at 3 mm may, at centimeter wavelengths, simply have such reduced amplitude that they are unidentifiable.

Perhaps the most striking feature of Fig. 2 is that the 3-mm and centimeter light curves display everything from high correlation to almost none. There is much activity in the 3C 84 3-mm data, but no obvious corresponding variability at centimeter wavelengths. The mean of the envelope containing the 3-mm measurements was at the same flux density levels as the centimeter data in the late 1960s, but decreased to about half the centimeter signal level by 1974. For 3C 120 there are possible correlations between some events at 3 mm and centimeter wavelengths; the mean of the envelope of the 3-mm data is of about the same intensity as the centimeter envelope mean. For OJ 287

Table II. Dates of Peaks of Possibly-Connected Events at Different Wavelengths[a]

Wavelength (mm)					Remarks
3.3	19.4	28	38	45	
		3C 84			
		--	1968.0:	--	
1968.6		--	1968.6?	--	Very broad
			1969.1	1969.4?	
			1969.65		
1969.4:		1969.6?:	1969.95	1970.1:	
1969.9:		1970.1?	1970.19?	--	
1970.3:	--	1970.5?	1970.65?:	1970.85??	
1971.4	--	--	--	--	
*1971.85	1972.2?:	1972.2:	1972.2:	1972.3:	
1972.4	--	--	--	--	
1973.05:		--	--	--	
*1973.26 1973.34		1973.6:	1973.75:		
--			1974.1		
		3C 120			
	1967.9	1967.9	1968.1		
1968.36:	--	--	--		
*1968.67:	1968.65:	1968.66:	1968.74:		
1968.85:	--	1969.11?	--		
*1969.35:	1969.6	1969.6	1969.6		
1969.7?	1970.25:	1970.3	1970.3	1970.4	
1970.75	1970.8?:	1970.9:	1970.9	1971.0	
1971.55:	1971.6:	1971.6:	1971.7	1971.6:	
*1972.7	1972.7:	19728	1972.85	1972.9	
*1973.05:	1973.2:	1973.2:	1973.2	1973.2	

[a]Meaning of symbols:

? Existence of peak uncertain.
: Date uncertain because peak very broad and/or poorly defined.
-- No reasonably connected event found.
* Event used in k-factor analysis (Sec. V.C).
No entry in the table indicates insufficient or no data.

Table II. (Continued)

Wavelength (mm) 3.3	19.4	28	38	45	Remarks
	1974.4:	1974.4	1974.4		
	1975.3:	1975.2:	1975.25		
			1975.55		
		OJ 287			
		1971.03:		1971.03?:	
1971.2:		1971.25:	—	1971.25?:	
1971.6?:		1971.85	—	—	
*1972.12:		1972.2:	1972.2	1972.2:	
1972.18		1972.22?	1972.3	—	Sharp drop
1972.8		—	—	—	
*1973.05:		1973.1:	1973.2	1973.2:	
1973.5:		1973.8	1973.9		
		1975.0:	1975.0		
		1975.4	1975.44		
		3C 273			
*1966.6		1966.8:	1966.8:		
≲ 1967.8:		1968.2:	1968.2:	—	
—	1969.3?:	1969.5	1969.6:	1969.7:	
1969.55			—		Sharp drop
1969.83			1970.2?		Sharp drop
1970.3:	—	—	—		
1970.7?:	—	—	—	1970.7?:	
*1971.8:	1971.8:	1971.8:	—	1972.0?:	Very broad
—	—	—	1972.3:	—	
1972.4:	—	—	—	—	
*1973.5:	1973.6:	1973.6	1973.9:		Very broad
	≳1975.5	1975.6:	1975.8:		
		BL Lac			
—		1968.75:	1968.75	1968.8:	
		1969.02	1969.10:	1969.12:	
		1969.2:	1969.2	1969.19	
—		—	1969.48	1969.49	
*1969.55:		1969.65	1969.66	1969.67:	
*1969.9:		1969.9:	1969.96:	1969.96	
*<1970.1:	1970.2:	1970.2:	1970.2	1970.21	
	1970.35?:	1970.35?	1970.4?:	1970.37:	
—	1970.7?	1970.7	1970.65?:	1970.67	
*≳1970.86:	1970.9?:	1970.88	≲1970.95	1970.9:	

Table II. (Continued)

Wavelength (mm)					Remarks
3.3	19.4	28	38	45	
	1971.1?	1971.10:	1971.08?:	1971.10?	
—			—	1971.20	
—			1971.35?:	1971.35?	
*1971.45::	1971.5:	1971.49	1971.49	1971.5	
*1971.83:	$\lesssim$1971.9	1971.83	1971.9:	1971.85:	
1972.1	1972.15?:		1972.14:	$\lesssim$1972.15	
1972.3:		1972.46?	—	—	
1972.6		1972.62	1972.6	1972.60?	
—		—	1972.74?:		
1972.8		1972.9	1972.93?:	1972.93?:	
1973.1		1973.12		—	
*1973.5	1973.4:	1973.52	1973.55:	1973.53	
1973.64	1973.7?	1973.72	1973.7		
		1973.9	1973.9		
	1974.4	1974.42:	1974.43		
	—		1974.63:		
	—	1975.23	1975.25?:		
		1975.43?:	1975.42?:		
	$\gtrsim$1975.55	$\gtrsim$ 1975.6	1975.6		

there are some correlations between 3-mm and centimeter events. The 3-mm envelope lies above the envelope of the centimeter observations in 1971 and 1972, but is at the level of the centimeter observations in 1973 and 1974. In 3C 273 there are millimeter to centimeter correlations at 1966.6, 1971.8, and 1973.5; there is also much 3-mm activity without obvious corresponding centimeter activity. The mean of the envelope of the 3-mm measurements has approximately half the intensity of the centimeter envelope mean. For BL Lac there is clear correlation between both envelopes and events at 3-mm and centimeter wavelengths. For all five sources, generally, the flatter the spectrum from 3 to 45 mm, the closer the correlation of activity.

For six of the BL Lac outbursts the spectral index was ≈ 0 between 3 and 45 mm. Standard models would suggest that the optical depth from 3 to 45 mm was very small. Events were thus simultaneously observable at all wavelengths. Conversely, for those objects where the correlation is poor or absent, the optical depth at centimeter wavelengths may be high enough that we don't see through the source to where the 3-mm activity is occurring. In other words, the 3-mm and centimeter emission are uncorrelated because they originate from different regions within the source.

The absence of correlation between the 3-mm and centimeter intensity variations in many instances is in contrast to the high correlation between short and long centimeter variations found by Andrew et al.[8] and the conclusion by Hobbs and Dent (1977) of high correlation between 3-mm and longer variations. (The approximately 85 sources considered by Andrew et al. and the ten considered by Hobbs and Dent include the five observed for this report.) That the Hobbs and Dent conclusion is based on undersampled data is clear from inspection of the lower half of Fig. 2, where their 3-mm data (red triangles) are plotted with our 3-mm light curves. Their data are simply too sparse to catch many of the 3-mm outbursts. The shortest wavelength data that Andrew et al. examined is the 19.4-mm data of Dent et al.,[9] which we show in the upper halves of Fig. 2. Yet we often do not find any correlation between the 3- and 19.4-mm light curves. Thus the correlation found at centimeter wavelengths often breaks down between 19 and 3 mm, at least for the five sources discussed here.

B. COMMENTS ON SELECTED EVENTS

To aid the reader, we draw attention to the following interesting events.

3C 120. Two 3-mm outbursts peak at 1972.2 and 1973.0. The associated centimeter outbursts are of nearly equal amplitude, while the 3-mm outbursts have greatly different amplitudes.

VLBI data[14] indicate a superluminal expansion of source components with a nominal zero separation time of 1972.4 ± 0.5. A major outburst in the 3-mm and centimeter light curves began at 1972.4; this 3-mm outburst is one of the two or three strongest 3-mm 3C 120 events. The next zero-separation time shown by the VLBI data, 1974.4 ± 0.2, coincides with a small centimeter outburst and a possible 3-mm outburst (the 3-mm data are limited).

OJ 287. The strongest OJ 287 3-mm outburst in our data peaked at 1972.17 ± 0.01; strikingly, this outburst was terminated by one of the sharpest drops observed at 3 mm, from 16 ± 2 to 7 ± 2 Jy in $\lesssim$ 7 days (see Table III). A partial recovery occurred during the next several weeks. There is an indication of a drop at 28 mm at 1972.22, but the data are too sparse to discern whether the decline was as rapid or as large as that at 3 mm. There are at least three oscillations of ~ 20% amplitude at 38 mm during the first three months of 1972 (see the insert in Fig. 2 of Aller and Ledden[23] for an expanded-scale plot of the 38-mm data). The descent portion of one of these oscillations began between 1972.16 = 29 February and 1972.17 = 3 March, i.e., at about the same time as the drop at 3 mm. No further 38-mm data were obtained until 15 days later, 18 March, at which time the signal was at another oscillation peak. Because the ≈ 50% drop at 3 mm was extraordinary, whereas the observed portion of the decline at 38 mm was not, one might speculate that the 38-mm signal actually declined much further during the 15-day gap in observations.

There is a 16% drop in the 28-mm data at 1972.07 = 26 January (see Table III). The expanded-scale plot of these data (Fig. 3, Ref. 17) shows that the drop occurred within 1 day. We do not know whether the decline continued--it was observed on the last day of a multi-wavelength monitoring campaign. The 28-mm measurements did not resume for 7 weeks. Kikuchi et al.[18] observed a

Table III. Quenchings in Extragalactic Variable Radio Sources

Source	Wavelength (mm)	Decline Amplitude	Quenching Time (Jy)	"Quiescent" Interval	Recovery	Reference
III Zw 2	60.0	$0.79 \pm 0.02 \rightarrow 0.66 \pm 0.03$	18–22 Mar 1972	?	Insufficient data	15
OJ 287	3.5	$6.7 \pm 0.8 \rightarrow 3.2 \pm 0.5$	20–23 May 1971	1 day	To 6.0 ± 0.4 Jy within 1 day	16
OJ 287	3.3	$15 \pm 2 \rightarrow 7 \pm 2$	3–10 Mar 1972	——	Partial, over next 0.2 y	This paper
OJ 287	28.0	$7.62 \pm 0.13 \rightarrow 6.42 \pm 0.09$	25–26 Jan 1972	——	——	17
OJ 287	72.0	$5.6 \pm 0.2 \rightarrow 4.6 \pm 0.1$	09.3–11.0 UT, 8 Feb 1973	$\approx$ 1 hr	To $\approx$ 5.0 Jy ($\approx$ 1.5 hr later)	18
3C 273	3.3	$36 \pm 4 \rightarrow 26 \pm 3$	18–22 Jul 1969	$\approx$20 days	To $\approx$ 38 Jy within $\approx$ 6 days	This paper
3C 273	3.3	$41 \pm 4 \rightarrow 20 \pm 4$	31 Oct–2 Nov 1969	——	To $\approx$ 30 Jy over next 0.4 y	This paper
3C 273	13.5	$41 \pm 1 \rightarrow 35 \pm 1$	$\approx$ 4 hrs on 22 Mar 1976	——	To $\approx$ 39 Jy within 1 day	19
3C 273	13.5	$38 \pm 1 \rightarrow 31 \pm 1$	$\approx$ 4 hrs on 29 Mar 1976	——	To $\approx$ 37 Jy within 3 days	19
Cen A	3.4	$22.5 \pm 2.0 \rightarrow 14.0 \pm 1.5$	27–28 Mar 1974	?	Insufficient data	20
OV–236	3.3	$6.7 \pm 0.6 \rightarrow 2.5 \pm 0.6$	4–7 Dec 1978	——	To 6.8 ± 0.3 Jy within 2 days	21
BL Lac	28.0	$13.8 \pm 0.3 \rightarrow 12.3 \pm 0.3$	29–30 Oct 1971	$\approx$ 6 days	None[a]	22

[a] This quenching could be interpreted as the decline portion of an outburst of $\approx$7 days total duration; however the decline was clearly more rapid than the rise.

decrease of ≈ 20% in OJ 287's 72-mm signal over 100 min on 8 February 1973 (=1973.11)--see Table III.

3C 273. The most surprising features are the two sharp drops at 3 mm: from ≈ 36 to ≈ 26 Jy within 4 days at 1969.55, and then after 20 days, recovery to ≈ 38 Jy within 6 days; and from ≈ 41 to ≈ 20 Jy within 2 days at 1969.83 (with gradual recovery over the next few months)—see Table III. Three observations were made during the ≈ 20-day duration of the first drop; each observation consists of 10 hours of integrations spread out over ≈ 5 days. Because the telescope was in operation on an almost round-the-clock basis, it is very unlikely that a systematic error was in effect for 20 days and yet had no observable effect on any of the several other objects monitored. Scrutiny of the original data, including the telescope diagnostic information recorded every 25 min (command and actual coordinates, temperature, relative humidity, refraction computation data, antenna tower tilt data, and pointing offsets), uncovered no anomalies. We can rule out Sun-in-sidelobe effects because the drops occurred when the Sun was far from 3C 273 (they were within 15 deg of each other during the interval 1969.71 - 1969.79); furthermore, our extensive Mercury observations show that the Sun-in-sidelobe effects for our antenna do not maintain the same amplitude and sign as the separation angle changes.

There is no clear evidence of corresponding drops in the centimeter data. For clarity, the 1969 and 1970 38-mm data are shown with an expanded intensity scale in the insert in the lower half of Fig. 2. Only Michigan data are shown because they are more precise and more frequent than the Haystack 38-mm data; when error bars are not shown, they are approximately the size of the symbols. [Efanov et al.[19] found declines of ≈ 15% and ≈ 20% in the 13.5-mm flux density of 3C 273 in only ≈ 4 hours on 22 and 29 March 1976, respectively; on both occasions the partial recoveries took 1 to 2 days. Gorshkov et al.[24] reported a 3C 273 decrease of ≈20% at 35 mm from 23 to 27 May 1969 (1969.40), but the published observational data are limited.]

Linear extrapolation of VLBI data[14] yields 1967.6 ± 0.4 as the start time of a superluminal expansion. This time does not coincide with the late 1965

time of the strongest 3-mm outburst ever observed in 3C 273. But it does coincide with a 3-mm outburst in late 1967 (inferred from the 3-mm decline observed in very late 1967/early 1968) and a centimeter outburst which commenced in late 1967. This 3-mm outburst, though poorly defined by the data, seems to be the second strongest event observed in 3C 273.

BL Lac. The coherence of the light curves of this source is the closest of the five sources presented here. The time lags between the peaks at successively longer wavelengths are very small (days to weeks). Although this behavior can be explained by the simple instantaneous-injection expanding source model, more complex models can also explain it.

C. RELATIONSHIP BETWEEN OUTBURST AMPLITUDE AND WAVELENGTH

We have examined the data of Fig. 2 for the relationship

$$\Delta S_\lambda \propto \lambda^k \qquad (1)$$

where ΔS_λ is the maximum amplitude above the quiescent level of an outburst at wavelength λ. For a simple expanding source model $k \approx -1.0$ (Ref. 25). However, Andrew et al.[8] found $\langle k \rangle = -0.4\,^{+0.2}_{-0.15}$ for 44 sources for which they had 28- and 45-mm data. Andrew et al. used an objective, rote technique (see footnote d, Table IV) to find ΔS_λ because of the difficulty in choosing a quiescent level (it is usually easy to define with confidence the maximum flux density); their rote technique is probably satisfactory because they had a fairly large sample. Because we have only five sources, we chose to make more thorough use of the data by estimating a quiescent level for each outburst. However, because the estimation is often quite arbitrary, we used two different procedures: a) linear interpolation between the troughs on both sides of the outburst, and b) extrapolation forward in time of the decay curve of any preceding outburst and backward in time of the growth curve of any succeeding outburst. The outbursts we analyzed are indicated by an asterisk in Table II. (These practical complications make it difficult to compare observations with synthetic light curves generated by models unless the synthetic curves include noise and overlapping events.)

Table IV. <k> Values[a]

Wavelengths considered (mm)	Procedure used: Interpolation[b]	Extrapolation[c]	Rote[d]
3.3 and 28	−0.29 ± 0.33 (n = 18)	−0.31 ± 0.15 (n = 14)	−0.44 ± 0.15 (n = 5)
3.3 and 38	−0.35 ± 0.24 (n = 16)	−0.37 ± 0.18 (n = 12)	−0.44 ± 0.09 (n = 5)
3.3 and 45	−0.39 ± 0.23 (n = 15)	−0.44 ± 0.18 (n = 13)	−0.45 ± 0.03 (n = 5)

[a] The statistical scatter is indicated by the cited standard deviations. The number of connected events analyzed, n, is given in parentheses.

[b] Outburst quiescent levels determined by linear interpolation between adjoining troughs in the light curves.

[c] Outburst quiescent levels determined by extrapolation of the decay curves of any preceding outbursts and of the growth curves of any succeeding outbursts. Fewer events are suitable for quiescent level determination by this procedure than by the linear interpolation procedure.

[d] The rote procedure of Andrew *et al*. (1978) wherein individual outbursts are not considered. The peak and quiescent levels are simply set equal to the maximum and minimum flux densities, respectively, observed over the entire monitoring period. Justification for this procedure is given by Andrew *et al*.

We calculated k for three wavelength intervals: from 3.3 to 28, 38, and 45 mm. The values of $\langle k \rangle$ for each interval and for the two different quiescent level determination procedures are contained in Table IV. The two procedures give essentially the same $\langle k \rangle$ values, although the values determined by the potentially more realistic extrapolation procedure have smaller standard deviations. The fourth column gives the values determined by the Andrew *et al.* rote procedure; they are not significantly different from the other values. We do not understand the surprisingly small scatter in the rote procedure results; perhaps it is fortuitous. To obtain an indication of the sensitivity to the adopted quiescent level, we computed k values with quiescent levels differing by $\pm$ 5%; the resulting changes in the $\langle k \rangle$ values were smaller than the uncertainties due to statistical scatter. From the Table we see that for the intervals 3.3 - 28, 3.3 - 38, and 3.3 - 45 mm, $\langle k \rangle = -0.4$ (std. dev. $\approx$ 0.2), in excellent agreement with the Andrew *et al.* value for 44 sources for 28 - 45 mm. Had our measurements of the 3-mm outburst amplitudes been, on average, larger or smaller by a factor of two (a very large error), we would have obtained $\langle k \rangle$ values of -0.7 or -0.1, respectively.

Caveats. Random errors may be present if we have made wrong connections between 3-mm and centimeter outbursts. Some 3-mm events may have been left out of the analysis because we were unable to identify their corresponding centimeter events; thus, we may be inherently biased toward less negative values of k.

Andrew *et al.* also analyzed 23 sources for which Altschuler and Wardle[12] had 37- and 111-mm data and found $\langle k \rangle = -0.4 \pm 0.15$. Thus we have the remarkable result that outburst amplitude varies approximately as $\lambda^{-0.4}$ from 3.3 to 111 mm, a wavelength ratio of 34. [This ratio is actually slightly larger because the emission observed at 3.3 mm is emitted at the source at $3.3/(1 + z)$ mm. We have neglected this relativistic correction because the largest z-value of our five sources is only 0.3 (OJ 287).] We know of no theory which predicts such a weak dependence of outburst amplitude on wavelength. Therefore this result may place a strong constraint on models of the variable emission of extragalactic radio sources.

D. TIME LAGS BETWEEN OUTBURSTS AT DIFFERENT WAVELENGTHS

On the assumption that the possible connections in Table II are real, we have calculated the time lags, if any, between outbursts at 3 mm and longer wavelengths. Although the epochs of event peaks are often poorly determined, we have treated them as accurate and precise, even when given to only one decimal place and when uncertainty is indicated, simply because no better data are available. Figure 4 shows the average time lag between possibly-connected events as a function of the difference between observing wavelengths. The vertical bars indicate the dispersion in values, not the standard error of the mean; the number of events in the sample is also indicated. The time lags are smallest in BL Lac (~ 0.06 y) and longest in 3C 84 (~ 0.2 to ~ 0.6 y). Within the limitations of the data, there is a suggestion that longer time lags are associated with larger wavelength intervals. Note that the two Seyfert galaxies in our sample (3C 84 = NGC 1275 and 3C 120) have longer time lags than the two Lacertids (OJ 287 and BL Lac).

E. SHARP DROPS (QUENCHINGS)

We have found in the Aerospace 3-mm data no outbursts on time scales of one to a few days. Neither did we find such rapid 3-mm outbursts in several searches with the NRAO 11-m antenna for intraday and interday variations of extragalactic sources[21]. But we have found in the Aerospace and NRAO data a number of rapid, large amplitude ($\gtrsim$ 30%) drops, or quenchings, on time scales of one to several days. Table III contains information on quenchings at various radio wavelengths in these and other sources; the tabulation is not meant to be exhaustive. Three quenchings have time scales of just a few hours.

Caveats. The definition of quenching and the selection of quenching events is arbitrary. We selected as quenchings those drops which are far more rapid than other increases and decreases observed in the given source at the given wavelength. We did not include, for example, any of the three OJ 287 drops of ~20% at 38 mm shown in the insert of Fig. 2 of Ref. 23 because their data show that ~ ±20% variations were common at that time in OJ 287. Had there been only one isolated rapid drop we probably would have included

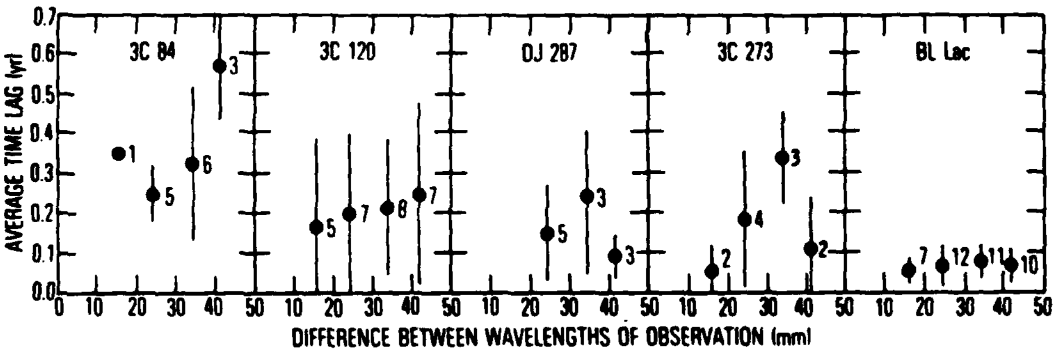


Figure 4 The average time lag between possibly-connected events as a function of the difference between observing wavelengths. The vertical bars indicate the dispersion in values, not the standard error of the mean; the numerals indicate the number of events in the samples.

it. To the extent that similar first derivatives may indicate similar physics, our selection criterion may be causing us to omit some physically interesting events. The sharpness of these drops is in marked contrast to the relatively slow decay of outbursts predicted by all published models we know of. The observations of quenchings thus place a new, and possibly strong, constraint on models of extragalactic sources. Perhaps eclipsing, obscuration, or rotation phenomena are involved.

VI. SUMMARY

Nine years of 3-mm observations of variable extragalactic radio sources have been presented and compared with centimeter-wave observations.

1) Useful information on extragalactic variable sources can be obtained with an antenna of only modest size.

2) Significant information on variations of extragalactic radio sources at short millimeter wavelengths is lost if temporal resolution of about one to three days is not achieved.

3) The degree of correlation between 3-mm and centimeter-wave variations ranges from high to low or almost non-existent. In general, the flatter the spectrum, the better the correlation.

4) The relationship between time lag and wavelength for possibly-connected outbursts appears to be characteristically different for different objects.

5) No pronounced 3-mm outbursts on a time scale of one to a few days were observed, but three sharp 3-mm drops or quenchings were. These Aerospace measurements, plus our measurements with the NRAO 11-m antenna, suggest that rapid drops at 3 mm may be more common than rapid rises.

6) The amplitudes of outbursts vary as λ^k , where $\langle k \rangle \approx -0.4$, from 3.3 to 111 mm, a factor of 34.

Results 5 and 6 may place important new constraints on physical models of extragalactic variable radio sources.

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LABORATORY OPERATIONS

The Laboratory Operations of The Aerospace Corporation is conducting experimental and theoretical investigations necessary for the evaluation and application of scientific advances to new military space systems. Versatility and flexibility have been developed to a high degree by the laboratory personnel in dealing with the many problems encountered in the nation's rapidly developing space systems. Expertise in the latest scientific developments is vital to the accomplishment of tasks related to these problems. The laboratories that contribute to this research are:

Aerophysics Laboratory: Launch vehicle and reentry aerodynamics and heat transfer, propulsion chemistry and fluid mechanics, structural mechanics, flight dynamics; high-temperature thermomechanics, gas kinetics and radiation; research in environmental chemistry and contamination; cw and pulsed chemical laser development including chemical kinetics, spectroscopy, optical resonators and beam pointing, atmospheric propagation, laser effects and countermeasures.

Chemistry and Physics Laboratory: Atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiation transport in rocket plumes, applied laser spectroscopy, laser chemistry, battery electrochemistry, space vacuum and radiation effects on materials, lubrication and surface phenomena, thermionic emission, photosensitive materials and detectors, atomic frequency standards, and bioenvironmental research and monitoring.

Electronics Research Laboratory: Microelectronics, GaAs low-noise and power devices, semiconductor lasers, electromagnetic and optical propagation phenomena, quantum electronics, laser communications, lidar, and electro-optics; communication sciences, applied electronics, semiconductor crystal and device physics, radiometric imaging; millimeter-wave and microwave technology.

Information Sciences Research Office: Program verification, program translation, performance-sensitive system design, distributed architectures for spaceborne computers, fault-tolerant computer systems, artificial intelligence, and microelectronics applications.

Materials Sciences Laboratory: Development of new materials: metal matrix composites, polymers, and new forms of carbon; component failure analysis and reliability; fracture mechanics and stress corrosion; evaluation of materials in space environment; materials performance in space transportation systems; analysis of systems vulnerability and survivability in enemy-induced environments.

Space Sciences Laboratory: Atmospheric and ionospheric physics, radiation from the atmosphere, density and composition of the upper atmosphere, aurorae and airglow; magnetospheric physics, cosmic rays, generation and propagation of plasma waves in the magnetosphere; solar physics, infrared astronomy; the effects of nuclear explosions, magnetic storms, and solar activity on the earth's atmosphere, ionosphere, and magnetosphere; the effects of optical, electromagnetic, and particulate radiations in space on space systems.

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